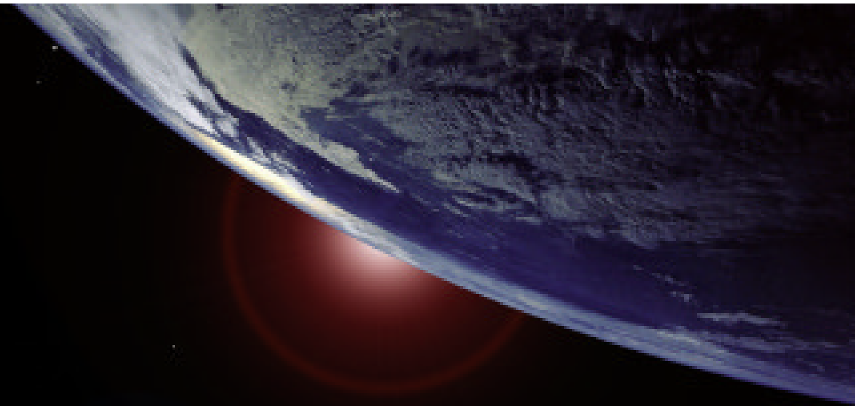

Really Advanced Propulsion Research

Presentation to

The Florida Chapter

Of The

American Institute of Aeronautics and Astronautics

By

John Cole

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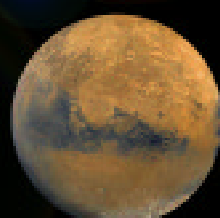
Marshall Space Flight Center



January 2000

STD5227

Really Advanced Propulsion Research

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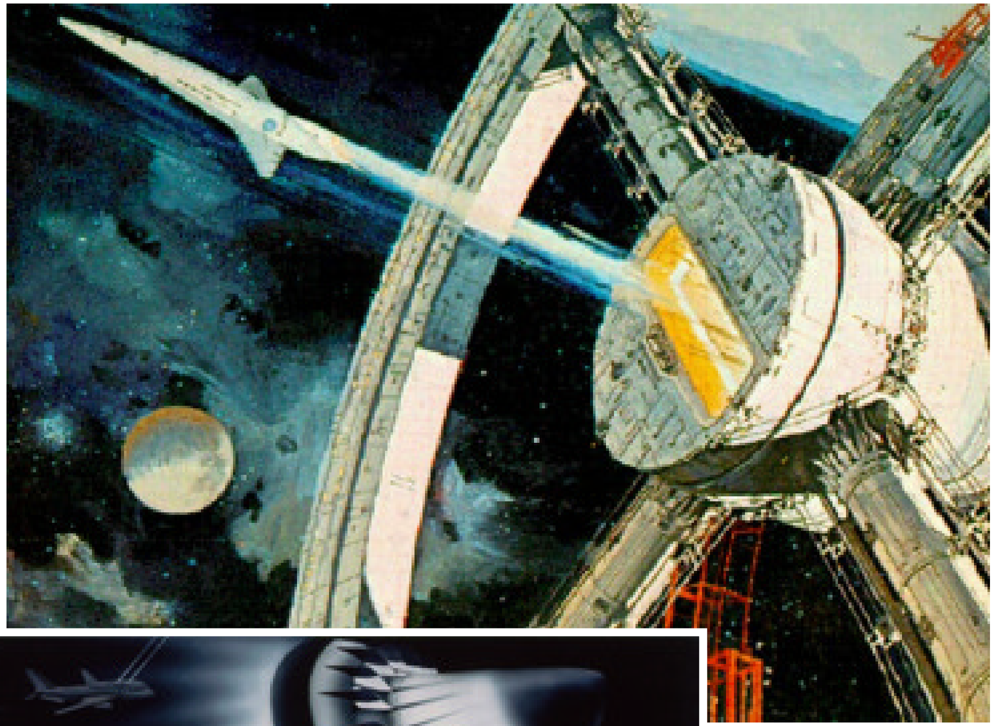
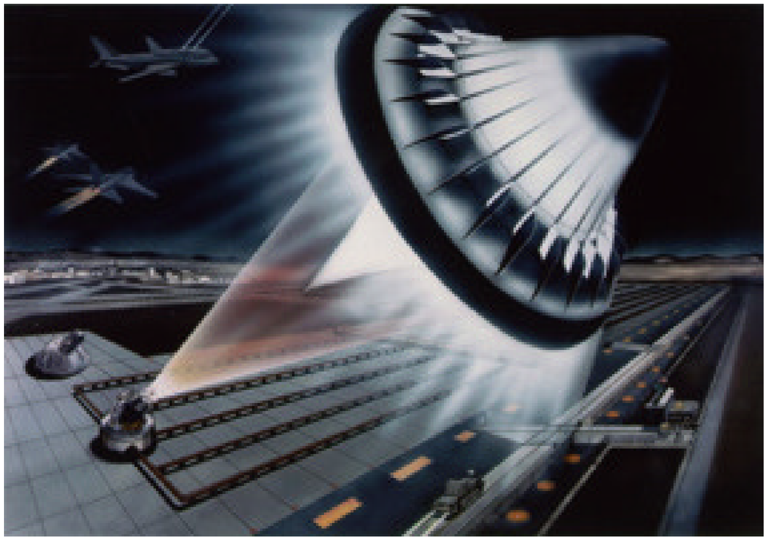
Objectives, Scope and Avenues for Research

- **Objectives of this Presentation**
  - To briefly discuss some of the current advanced propulsion research
  - What it is, how it works, expected benefits, and who is doing it.
- **Research Objectives**
  - Significantly improve safety and cost of space transportation
  - Reduce trip time for in-space missions
  - Enable new missions
- **Scope of potential mission applications include Earth to orbit, In-space transfers, Interplanetary, and Interstellar precursors**
- **Avenues**
  - Advanced Fuels and Cycles
  - Use of Off-Board Resources
- **Most of these concepts are 30 - 40 years old, but now we have new materials and analysis tools**



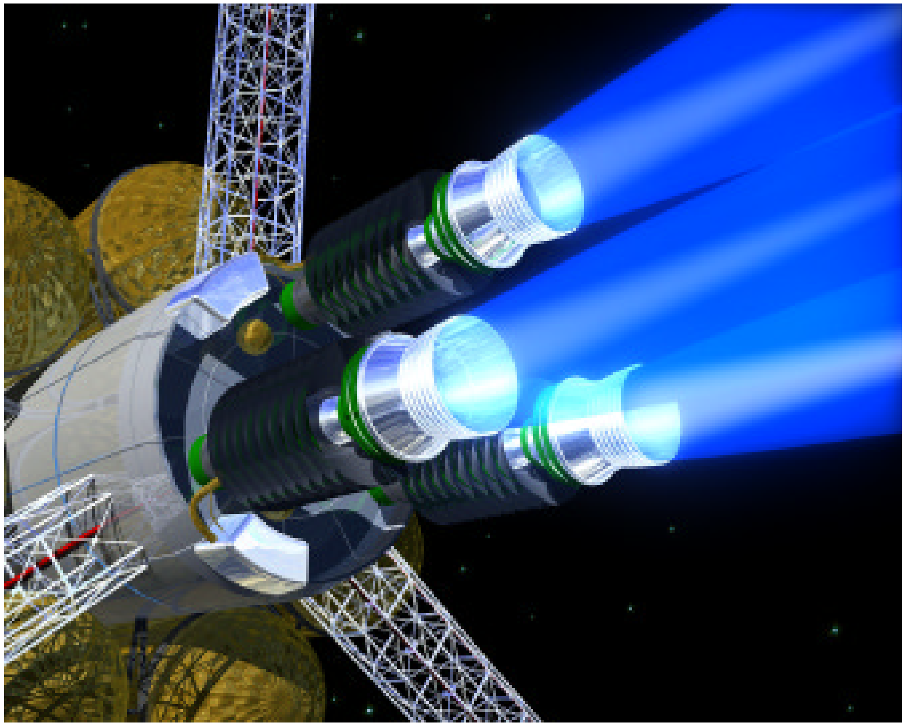


Safety First

- **Whatever space faring vehicles are built in the future they must be "SAFE"**
  - Safe for Flight Crew and Passengers
  - Safe for the Ground Crews, and Space Operations Crews
  - Safe for the local and global population
  - Safe for the Environment and Eco-system
  - Safe for our children and future populations
- **As a Goal : These future vehicles must be "AirLine Safe"**
- **We believe that this will also lead to improved mission success**

Performance Measures

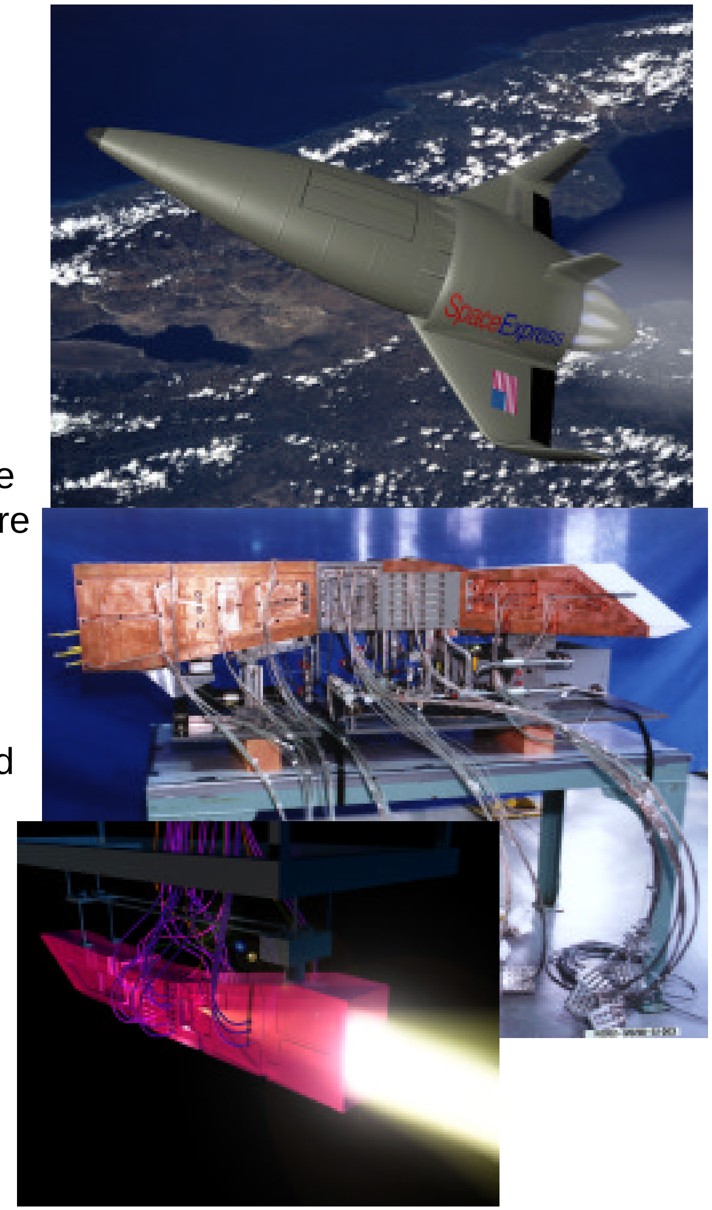
- **Some terms that will be used to describe performance:**
  - Specific Impulse (Isp) :
    - The number of seconds that one pound of fuel will provide one pound of thrust.
    - This exact number depends on the type of engine, the type of fuel, and operating conditions.
    - The Shuttle main engines (LOX / H2) has about Isp = 450 seconds
    - The Shuttle solids are about 280 seconds.
  - Propellant Mass Fraction
    - The fraction of the vehicle that is propellant.
    - The Shuttle is about 0.88
  - Thrust to weight ratio
    - Engine thrust divided by engine weight
  - Trip Time
    - Time for a one way trip



Advanced Propulsion Concepts Database

Advanced Chemical - Engines

- **Rocket Based Combined Cycle (RBCC)**
  - The concept looks like a small rocket engine in a larger tube, open at both ends.
  - The engine has 4 operating modes
    - In the Ejector Mode the rocket engine works like the compressor stage of a jet engine. The high velocity rocket exhaust entrains and compresses air flowing into the open fromt end. This air burns fuel like the after burner of a jet engine.
    - In the Ram Jet Mode the rocket is turned off when the vehicle velocity reaches about Mach 2. At that point the ram pressure is sufficient to compress the inlet air.
    - In the Scram Jet Mode the secondary fuel injection is moved forward to allow adequate time for fuel and air to mix before burning to provide thrust.
    - The Rocket Mode begins when the vehicle runs out of air and re-lights the rocket.
  - By using off-board resources, air, the vehicle may be able to be lighter weight, lower cost, and have more design margin for building in reliability and safety.
  - Boeing (Rocketdyne) and Aerojet have ground test engines currently in test.



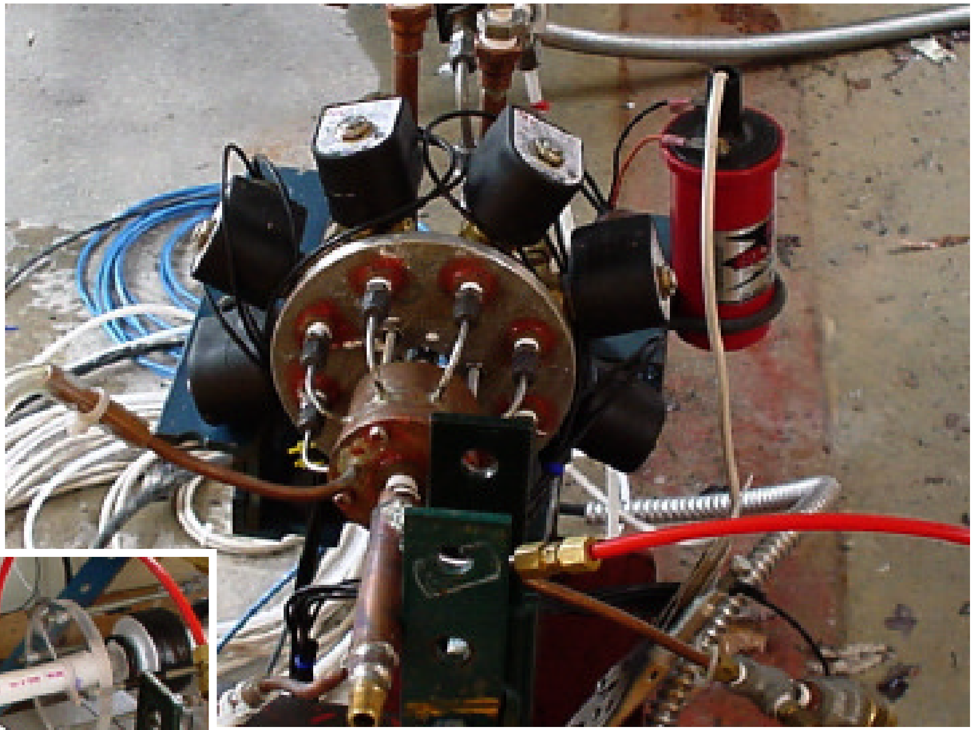
Advanced Chemical - Engines, Cont'd

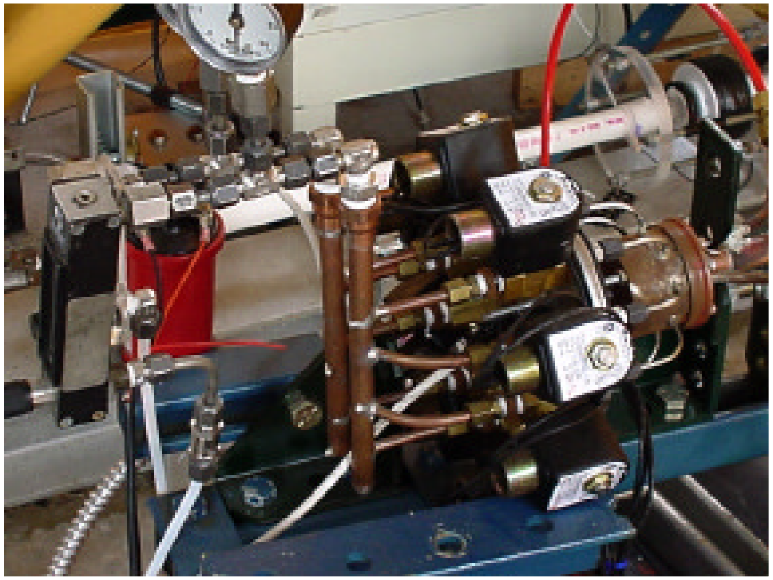
- **Liquid Air Cycle Engines (LACE)**
  - The cooling properties of liquid hydrogen can be used to liquefy air which can be used as oxidizer in a rocket engine.
  - However, only about 20% of the required oxidizer can be produced this way. Since the oxygen typically weighs six times as much as the hydrogen, a 20% reduction in on-board oxygen is significant.
  - This 20% may be enough to fire the ejector rockets in an RBCC.
  - Oxygen must be carried to operate the rockets when the vehicle leaves the atmosphere.
  - The oxidizer savings must be offset by the weight of the heat exchanger and de-ice systems.
  - The Japanese are currently experimenting with LACE systems.

- **Deeply Cooled Air Rocket/Ramjet Engines (DCARE)**
  - Rather than liquefying air, performance can be improved by deeply cooling the air, significantly increasing the air available to be pumped as a gas into the rocket engine.
  - The excess hydrogen is then consumed in a ramjet engine mounted in combination with the rocket.
  - MSE, Inc. in Montana is currently working this concept.

Advanced Chemical - Engines, Cont'd

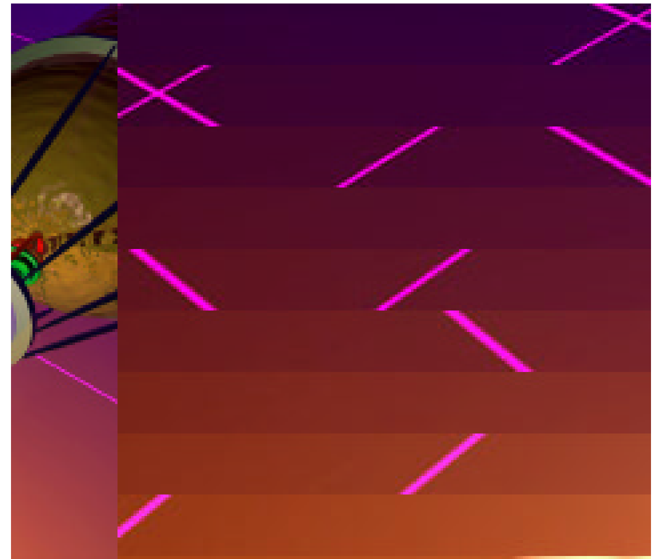
- **Pulse Detonation Rocket Engines (PDRE)**
  - The engine is essentially a straight pipe closed at one end and open at the other.
  - Similar to an automobile engine a pulse of fuel and oxidizer is injected into the tube and ignited with a spark plug.
  - The expanding gas provides pressure on the closed end and exits the open end providing thrust. Then the cycle is repeated.



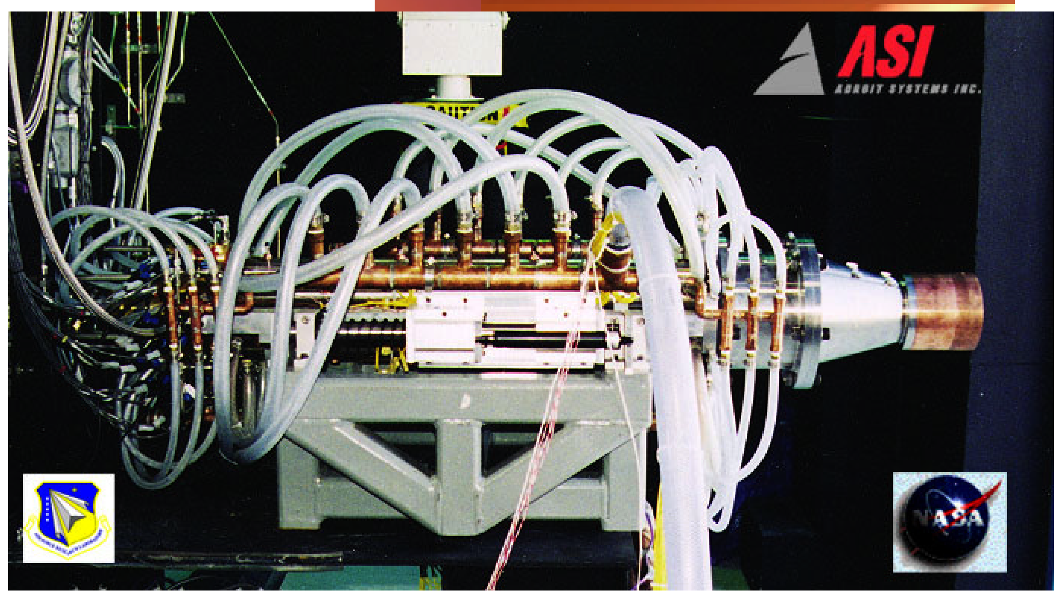


PDRE at MSFC

Advanced Chemical - Engines, Cont'd



- **Pulse Detonation Rocket engines (PDRE) Cont'd**
  Comparison
  - In a normal constant chamber pressure rocket engine:
    - Propellant is fed into the engine at a pressure higher than the chamber presure, requiring high pressure pumps.
    - Expansion of the fuel at constant pressure represents energy that cannot be used for thrust. This is true for all Brayton cycle engines.
  - In a PDRE:
    - The fuel is injected at low pressure thus requiring much lighter weight and less expensive pumps
    - A detonation wave traveling at ten times the speed of sound completes the combustion before the gas has time to expand.
    - This Humphries cycle avoids the PdV energy losses and releases about 10% more energy from the fuel for thrust.
    - The simple geometry and use of automotive components may yield very low costs.



  - For more information, please see:
    http://www.highway2space.com/newsarchive/pulse.html

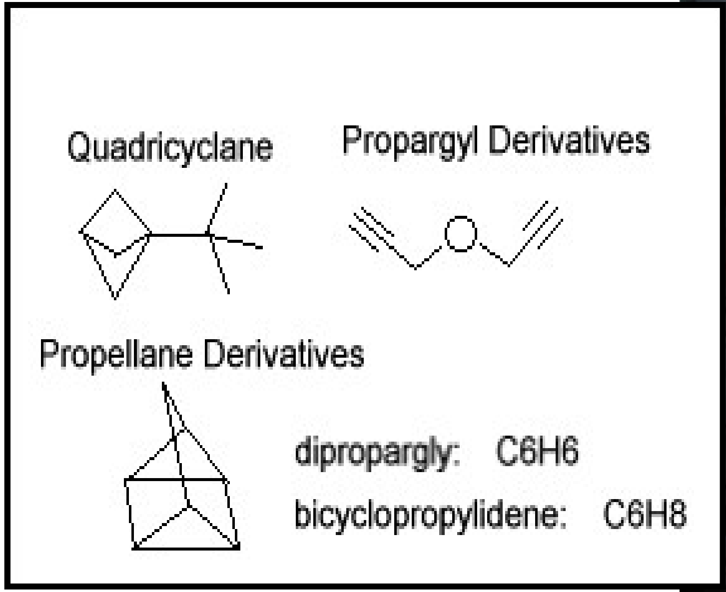
Advanced Chemical - Engines, Cont'd

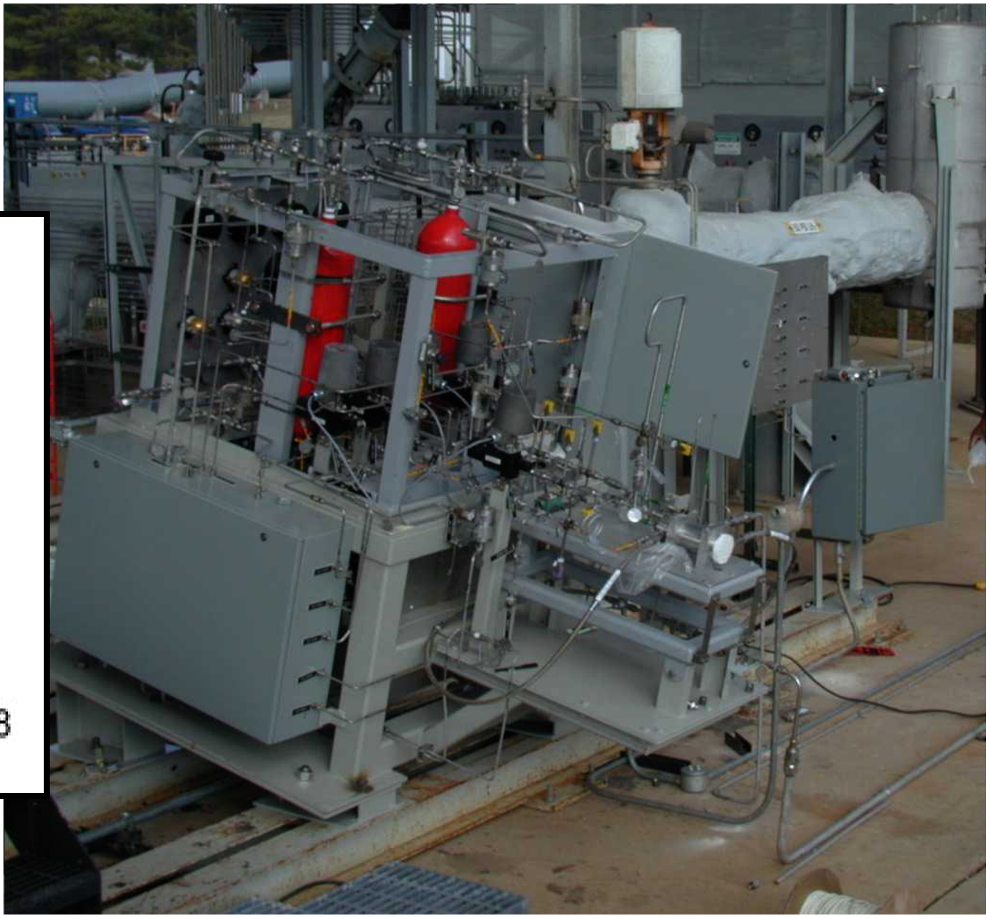
Gun Launch to Space

- Gun launch may be the lowest possible cost for access to space by chemical or electromagnetic systems.
- This is because the launch system stays on the ground avoiding the costs of carrying propellants to burned on the way.
- Several concepts have been identified which may, just barely, be able to provide the 8Km/s required. These include a multi-stage light gas gun, a blast wave accelerator, and a coil gun.
- There are several problem areas that need to be addressed:
  - Some method of orbit circularization is required to avoid reentering the earth's atmosphere.
  - The launch loads are 30,000 to 50,000 gees, allowing only small robust payloads.
  - Concepts for rapid and low cost turnaround.
- These concepts are being pursued by the Army, Lawrence Livermore, and the University of Texas.

Advanced Chemical - Advanced Fuels

- **Strained Ring Hydrocarbons**
  - New hydrocarbon fuels developed by the Air Force Research Lab at Edwards (AFRL-E)
  - They use strained ring molecular structures to increase Isp by 10% and increase the specific gravity by 25%
  - Some of these fuels will be tested in a small rocket engine at MSFC this year.





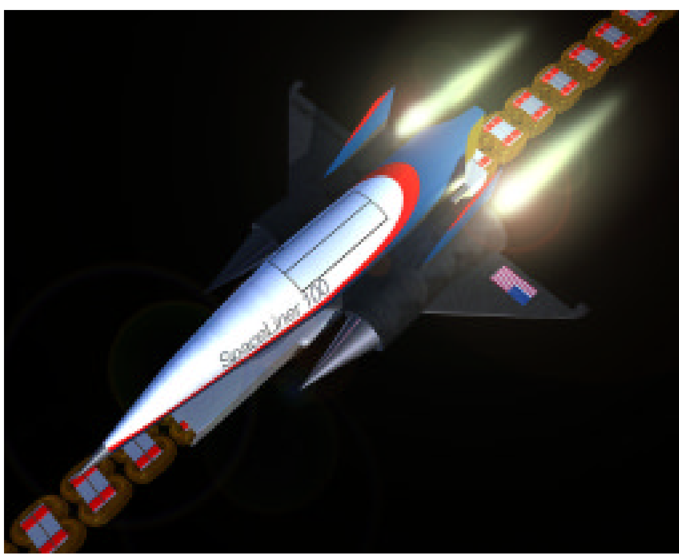
Advanced Chemical - Advanced Fuels Cont'd

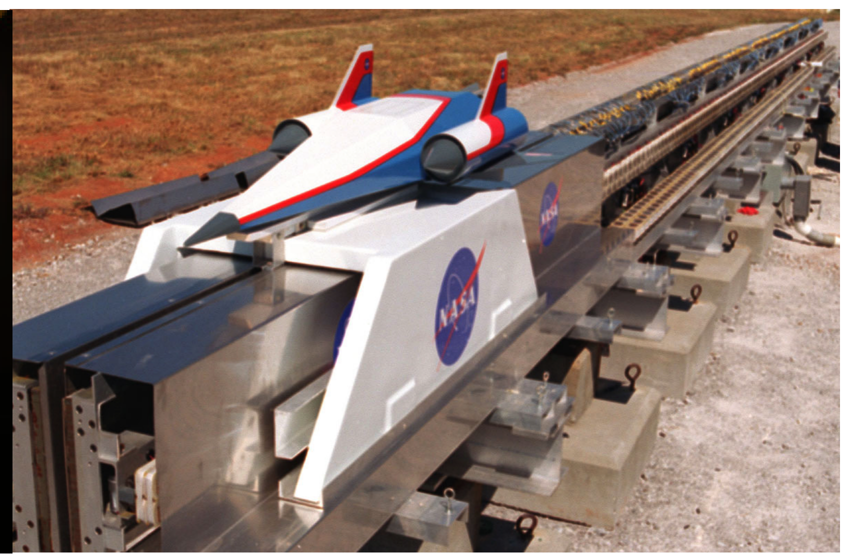
- **Exotic Fuels**
  - Metallic Hydrogen: Isp > 1100 sec, produced by Lawrence Livermore several years ago, lasted about 50 ns.
  - Metastable helium: Isp > 1200 sec, Never produced, probably a myth.
  - Recombination Energy: Isp > 550 sec.
    - Atoms of carbon or boron when allowed to recombine into molecules release ten times as much energy as can be obtained from combustion.
    - AFRL-E has demonstrated stabilization of milligram quantities of the atoms by freezing them in solid hydrogen snow.
    - It is a very energetic and unstable monopropellant.
    - Glenn Research Center is investigating methods of producing larger quantities for tests by using a liquid helium carrier for the solid hydrogen snow.

Electromagnetic Propulsion Concepts

Mag Lev Launch Assist

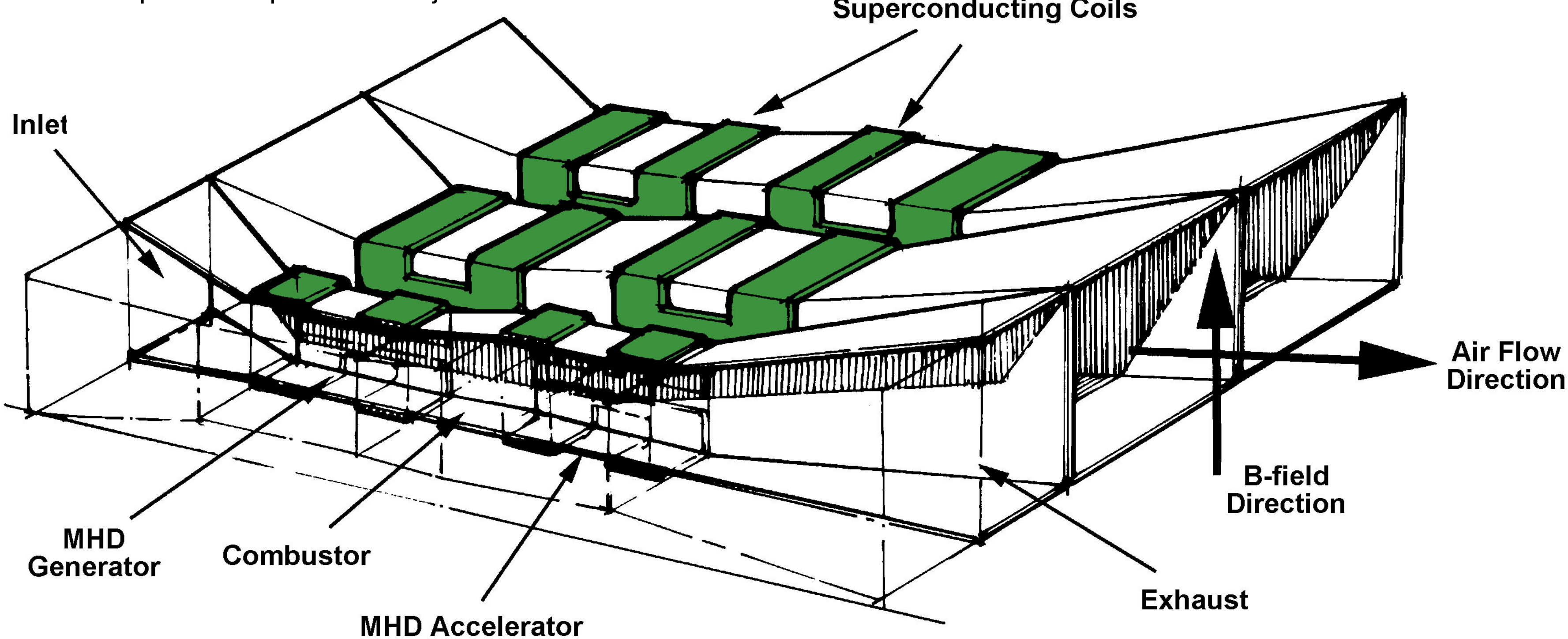
- Strap-on solid boosters are a common form of launch assist with obvious benefits.
- The Mag Lev launch assist concept accelerates a sled down a horizontal or gently rising two mile track.
- A two stage RBCC launch vehicle is released from the sled when the velocity reaches 400 miles/hr.
- Track length permits contingent recovery of the sled and vehicle in case of launch abort.
- This ground based reusable launch assist system can reduce the vehicle size by more than 20% for the same payload delivery capability.
- Current plans are to build a Mag Lev demo track at KSC in the next several years.
- Those interested in this concept include PRT, Inc. of Chicago, Lawrence Livermore National Labs (LLNL)., Foster Miller, Inc. of Boston and Boeing (Rockwell)
- Two small tracks are operating at MSFC and one at LLNL, all with different technology.





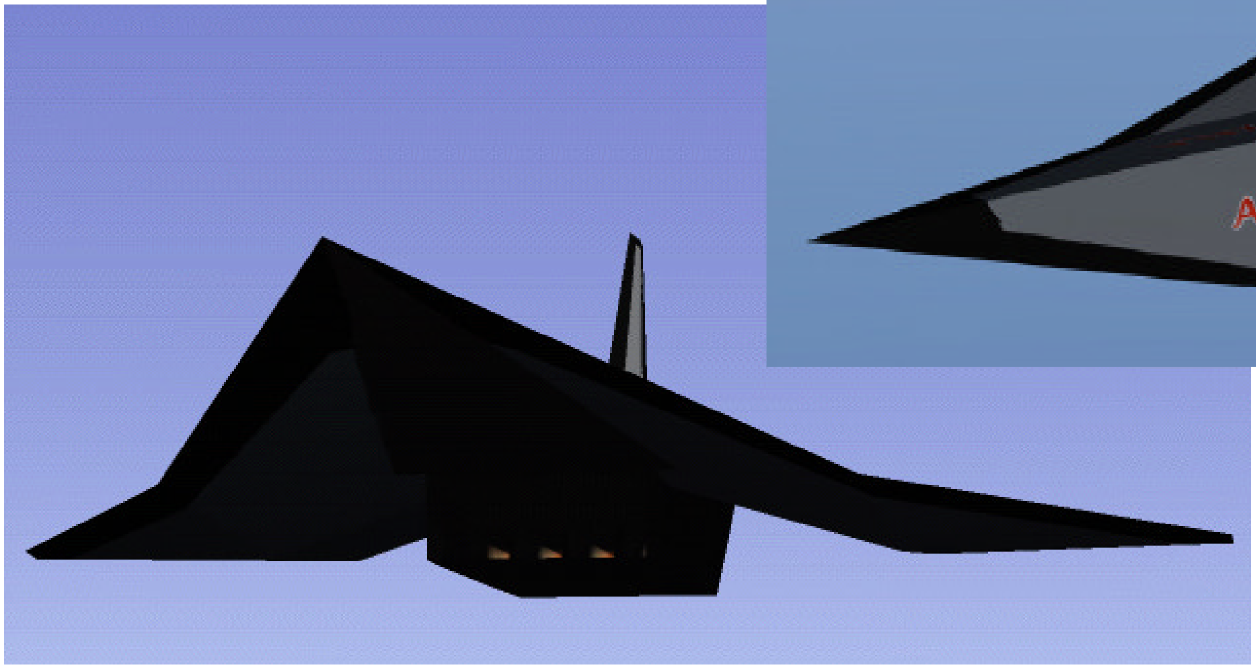
Electromagnetic Propulsion Concepts, Cont'd

- **AJAX, a Russian Hypersonic Aircraft Concept**
  - Principles of Magnetohydrodynamics (MHD)
    - High velocity ionized gasses flowing through a magnetic field will be diverted in a direction perpendicular to the field.
    - The electrons and negative ions are diverted in one direction and the positive ions in the opposite direction.
    - Electrodes placed to collect these charged particles can generate electric power while decreasing the fluid velocity. This is an MHD generator.
    - Power from an external source to the electrodes can accelerate the flow.
  - Since a Ramjet has twice the efficiency of a scramjet the Russians propose to use MHD to make hypersonic flow look like optimum supersonic ramjet conditions.



Electromagnetic Propulsion Concepts, Cont'd

- **AJAX, a Russian Hypersonic Aircraft Concept (Cont'd)**
  - An MHD generator and flow ionizer is placed in the engine inlet to slow the gas flow to ideal ramjet conditions. The electrical power from the MHD generator is sent to an MHD accelerator located at the ramjet exhaust to increase thrust.
  - The concept also uses MHD and weakly ionized gas effects to reduce drag and create a virtual inlet that doubles the air flow into the ramjet.
  - Mass of the magnets, electrodes and ionizer are big problems.
  - These types of concepts are being studied by NASA-ARC, Anser Corp. and AFRL.



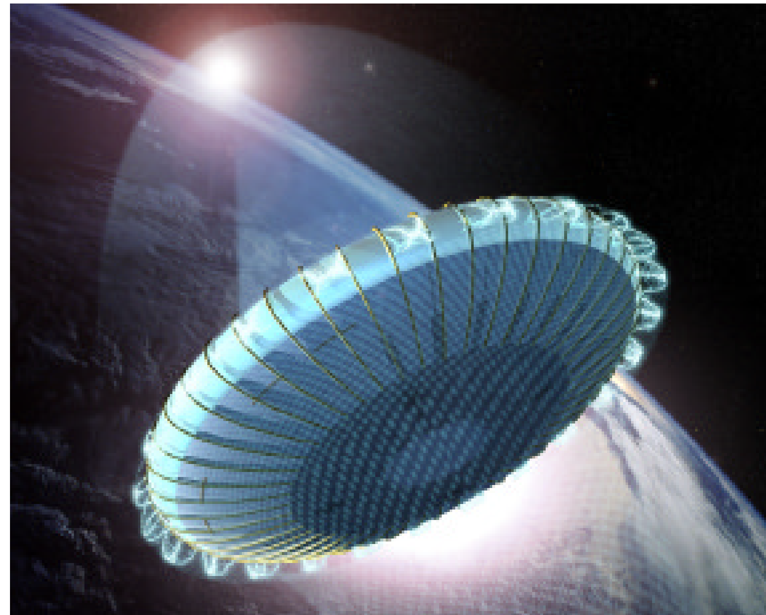
Electromagnetic Propulsion Concepts, Cont'd

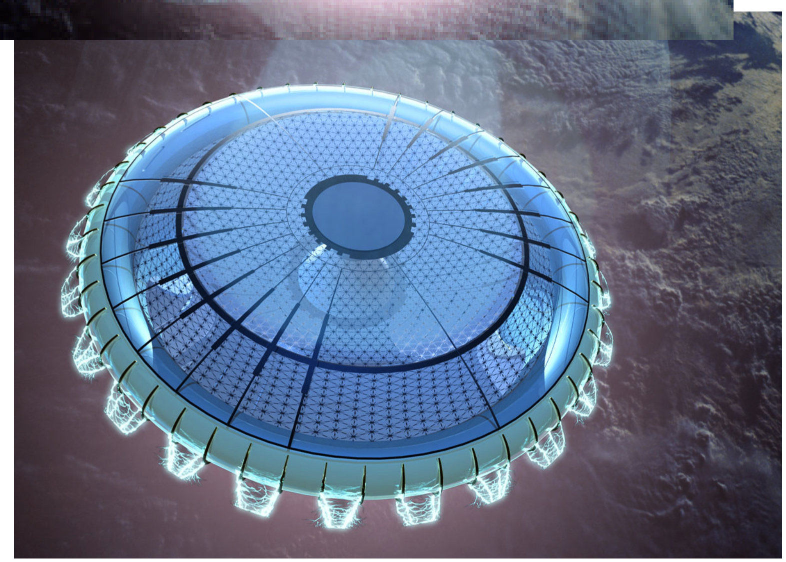
- **Laser Beamed Energy Propulsion - The Laser Lightcraft**
  - A ground based beam of pulsed laser light is directed onto the optics of a small flight vehicle.
  - The laser pulse is tightly focused into a vehicle reaction chamber where it initiates a laser supported detonation, rapidly heating the air or fuel to white hot temperatures.
  - The hot gas expands through a nozzle to provide thrust. Air or fuel is refreshed for a new pulse.
  - Recent free flight tests of a 30 gram spin stabilized vehicle have reached a height of 125 feet using a 10.6 micron CO_2 laser at 10 KW power at 20 pulses per second at White Sands, NM.
  - Estimates are that one megawatt of laser power is required for each kilogram of payload to orbit.
  - Atmospheric blooming may limit ultimate payloads to several hundred Kg.
  - Research is primarily by Dr. Leik Myrabo at Renssalear Polytechnic Institute in Troy, NY, AFRL-E, MSFC and the Army at White Sands.

Electromagnetic Propulsion Concepts, Cont'd

Microwave Beamed Energy Propulsion - The Microwave Lightcraft

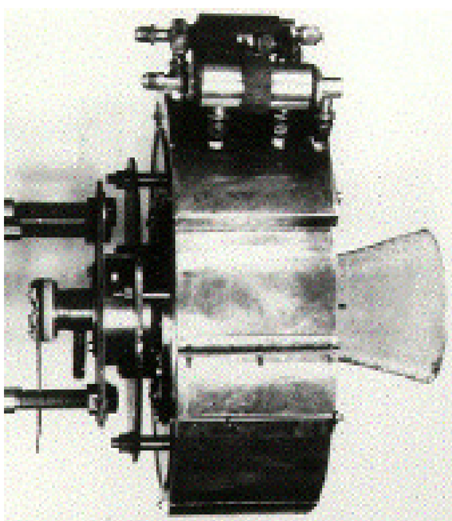
- The concept is to push a lenticular shaped helium balloon into space using an intense ground based microwave beam. This hypersonic helium balloon has many technical challenges.
- Since microwave pressure alone is not sufficient, the microwave energy reaching the vehicle must be
  - Converted into electricity with a rectenna to power an electric propulsion system or
  - focused to provide air detonation similar to the Laser Lightcraft.
- Electric propulsion concepts include
  - An ion wind system
  - An MHD slipstream accelerator with a focused microwave air spike for ionization.
- A Canadian company is providing a high performance rectenna
- Renssalear Polytechnic Institute is testing an MHD slipstream accelerator.
- Ames Research Center is performing a computational analysis of the slipstream accelerator.
- UAT, Inc. provided a a pressurized toriod and will attach the skins for a small static test article.
- Langley Research Center if looking at materials for this hypersonic helium balloon.
- Marshall Space Flight Center is performing a systems analysis of the concept.
- So far the concept still looks feasible using existing technology and can be scaled to handle large payloads.

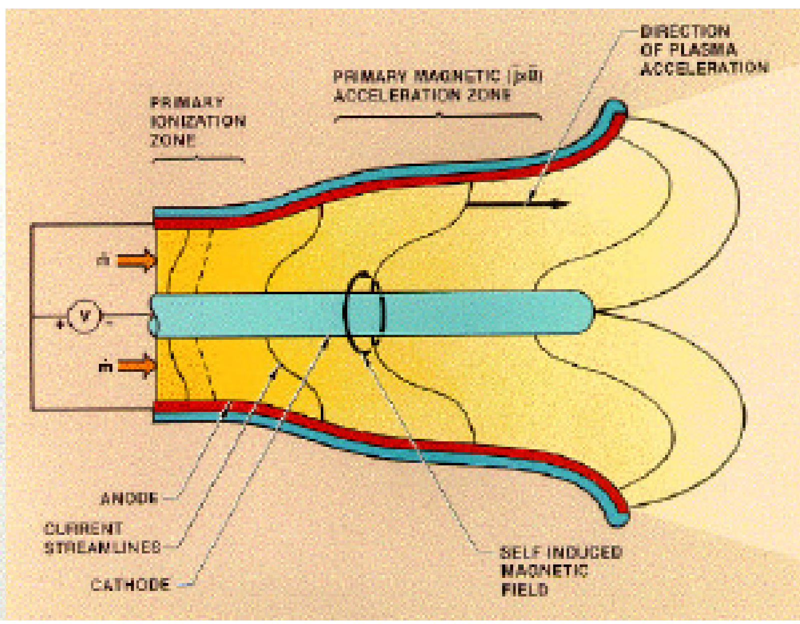


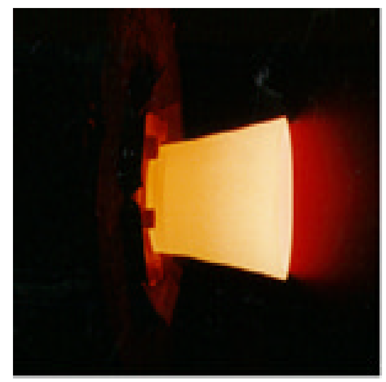


Electromagnetic Propulsion Concepts, Cont'd

- **High Power Electric Engines**
  - It may be possible to dramatically reduce trip times for manned missions beyond Mars by using megawatt class electric engines powered by nuclear reactors.
  - Two types of electric engines appear capable of being scaled up to megawatt levels
    - **Magnetoplasmadynamic (MPD) Thruster** -
      - An intense electric arc struck between coaxial electrodes creates a very high magnetic field behind the arc.
      - This magnetic field pushes the arc and a small amount of ionized propellant to high velocity out the open end of the engine providing Isp > 5000 sec.
      - This concept features very low weight, but suffers from electrode erosion.
      - This concept is being investigated by JPL, Princeton, and GRC.



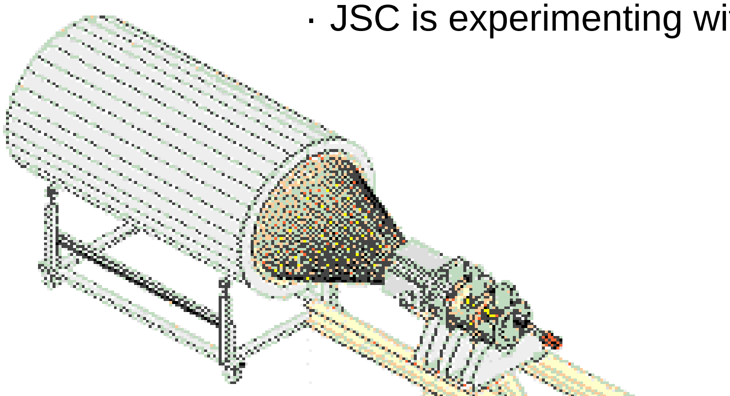


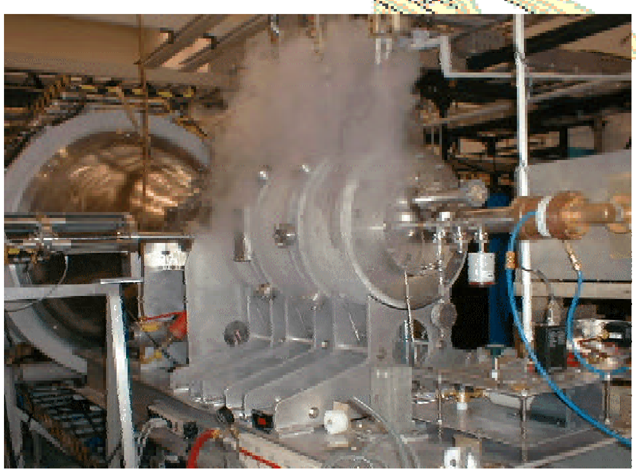


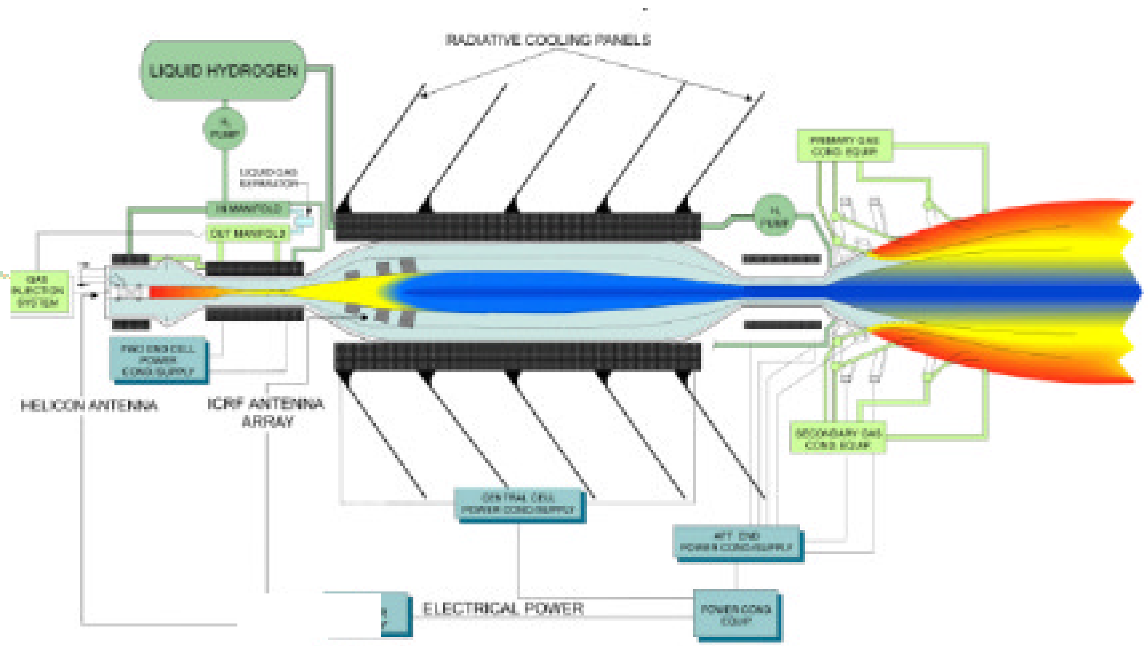
30 kW MAI Li thruster delivered to Princeton University for testing With JPL feed system

Electromagnetic Propulsion Concepts, Cont'd

- **High Power Electric Engines (Cont'd)**
  - **Plasma Rocket** -
    - Microwave energy is used to heat a plasma to very high temperatures in a magnetic bottle with mirror magnets at each end.
    - The most energetic ions located close to the axis will leak through the mirrors producing thrust with Isp > 5000 s. Isp can be increased by reducing thrust.
    - Current magnet technology makes the concept heavy, but is has no electrodes.
    - JSC is experimenting with versions called VASIMR and RTD.

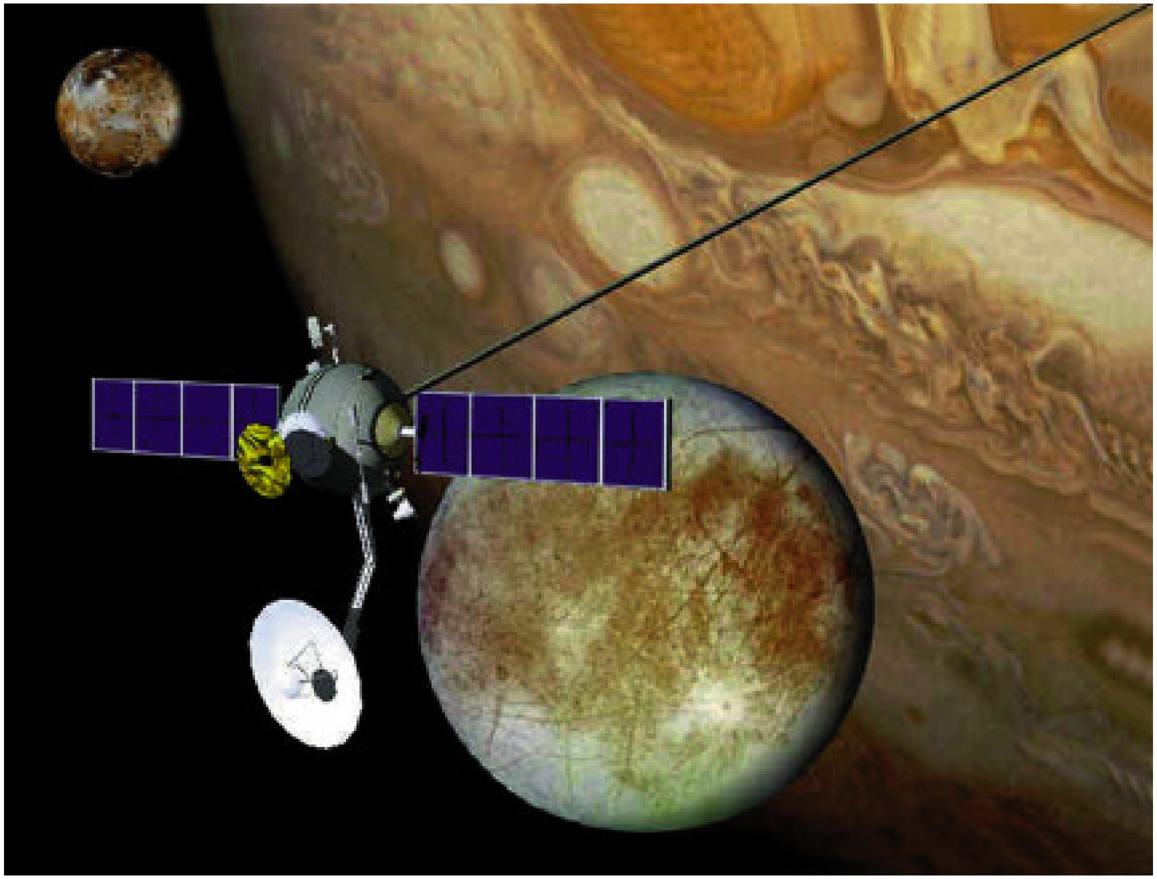




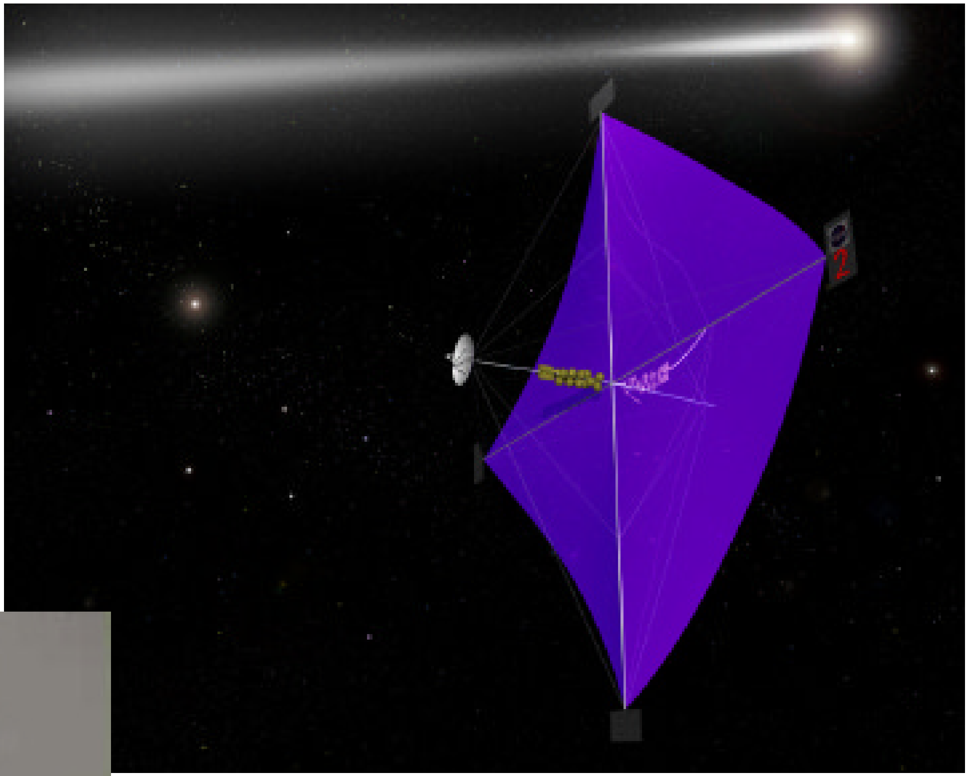


Electromagnetic Propulsion Concepts, Cont'd

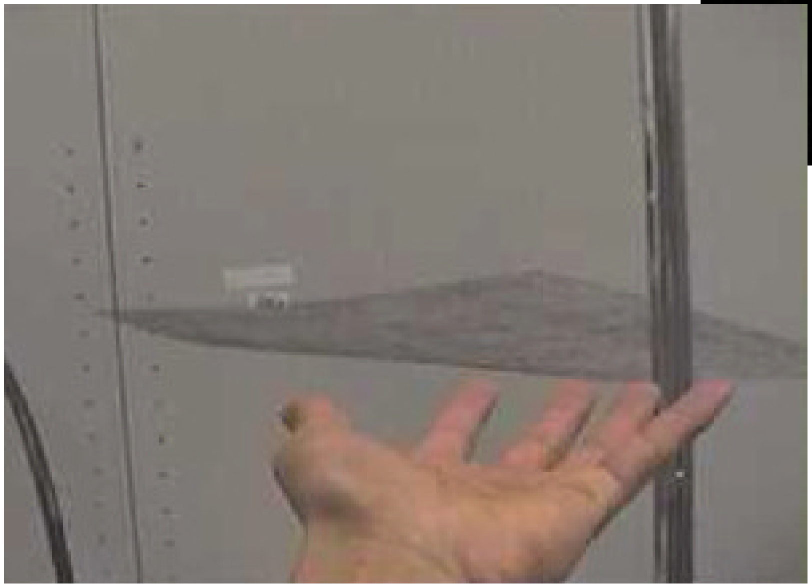
- **Electrodynamic Tethers**
  - A long conducting tether passing through the earth's magnetic field generates an electric potential between the ends of the tether.
  - Plasma contactors permit current to flow through the space environment to and from the ends of the tether.
  - The energy generated by the current flow comes at the expense of orbital altitude.
  - Additional energy from solar arrays can reverse the process and raise the orbit altitude. This is a propellant-less propulsion system being pursued by MSFC.



Electromagnetic Propulsion Concepts, Cont'd



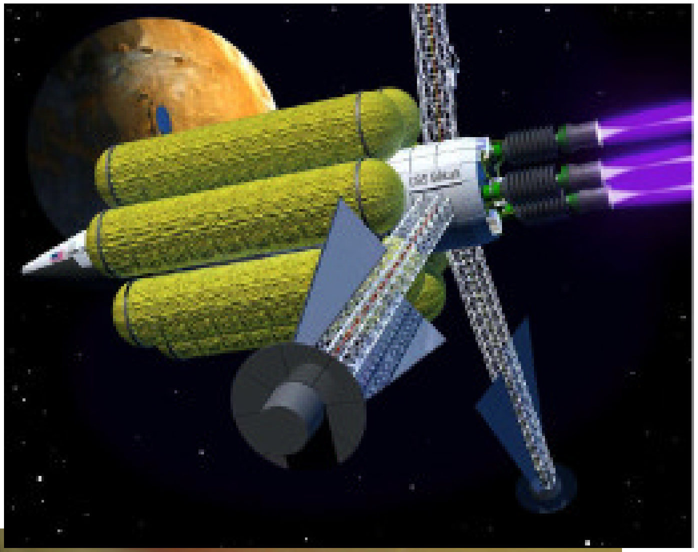
- **Sails**
  - Photon pressure from the sun or a laser on a large area of ultra light weight film will produce a small but significant acceleration on the film.
  - The angle of the sail with respect to the source can either add energy to the orbit or reduce it.
  - One effective concept after earth escape is to move closer to the sun to increase the solar flux and then depart using the increased acceleration.
  - JPL is investigating missions using solar sails.

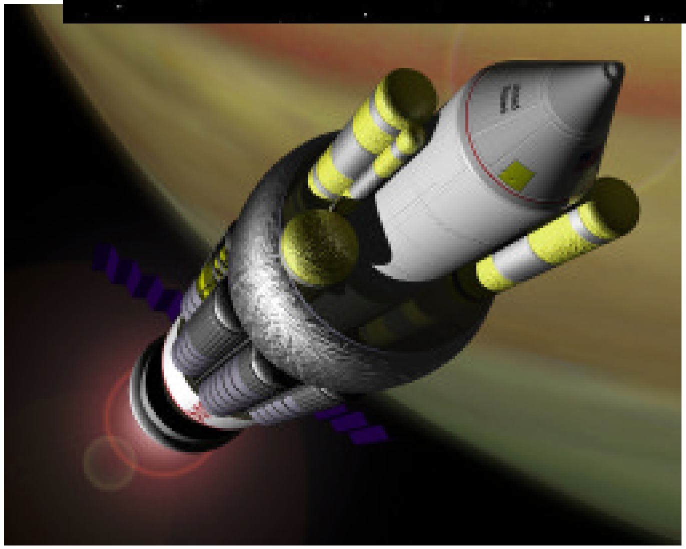


Carbon fiber μ-truss fabric (1 gm/m^2, 2 mm thick)

Nuclear Propulsion Concepts

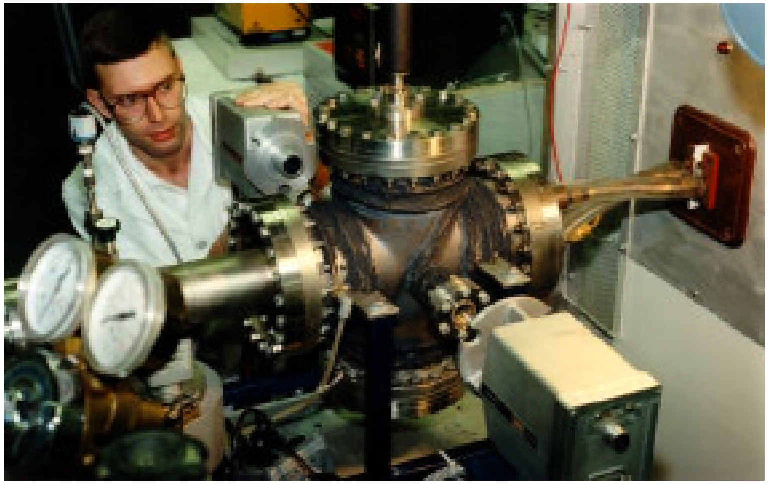
- **Nuclear Thermal and Nuclear Electric**
  - **Nuclear Thermal Rockets (NTR)** typically flow hydrogen gas through the reactor core to heat the gas which provides thrust by expanding through a nozzle. This system provides high thrust with Isp > 800 s.
  - **Nuclear Electric Propulsion (NEP)** typically uses a nuclear reactor to generate electric power (similar to a submarine) which is used to power an electric propulsion system. Low thrust with Isp >> 5000 s.
- **Why sould we consider Nuclear Propulsion????**
  - Chemical propulsion systems have been pushed to limit. Maybe another few % left.
  - Nuclear could put us on a new growth path with a factor of 1,000,000 improvement in specific energy, a factor of 10 to 100 in ISP.
  - In the event the nation decides to pursue this, to be at least a little prepared, a small amount of research now is appropriate.
- **Some Nuclear Concerns**
  - Safety - If we cannot make it "Air Line Safe" we will not propose to build it
  - Testing nuclear systems has been too expensive. Low cost testing is needed.
  - Nuclear weapons technology proliferation -
    - Can we separate propulsion research and weapons?
    - Some old nuclear propulsion concepts definitely cross the line!!



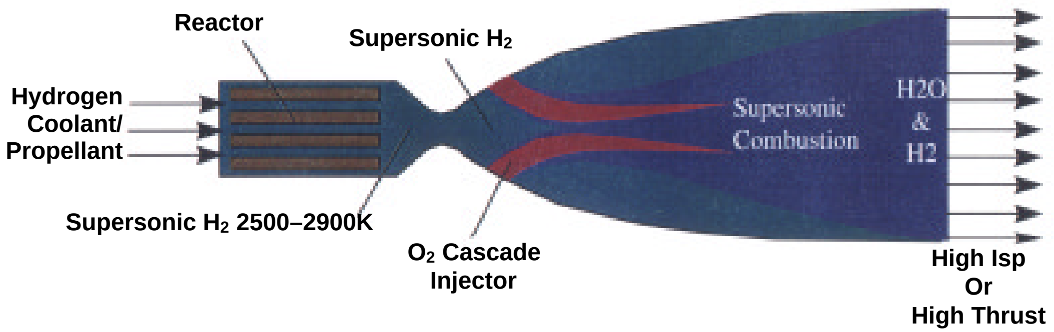


Advanced Nuclear Propulsion Concepts

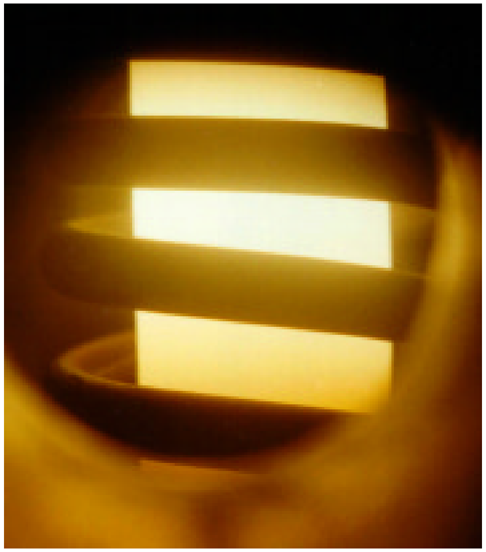
- **High Temperature Nuclear Fuels**
  - Solid core nuclear reactor performance is limited by the melting point of the nuclear fuel
  - Exotic alloys, sometimes called ribbon fuels, developed by Russia and further developed by the University of Florida, may allow Isp increase from 800 sec. to greater than 1000 sec.
- **LOX Augmented NTR**
  - To assist in escaping the earth's gravitation well liquid oxygen can be injected into the NTR nozzle to increase thrust at the expense of Isp.
  - When the gasses in the nozzle expand and the temperature falls below the molecular dissociation level the oxygen will chemically react with the hydrogen to maintain pressure a little longer.



Processing of a Nuclear Fuel Sample

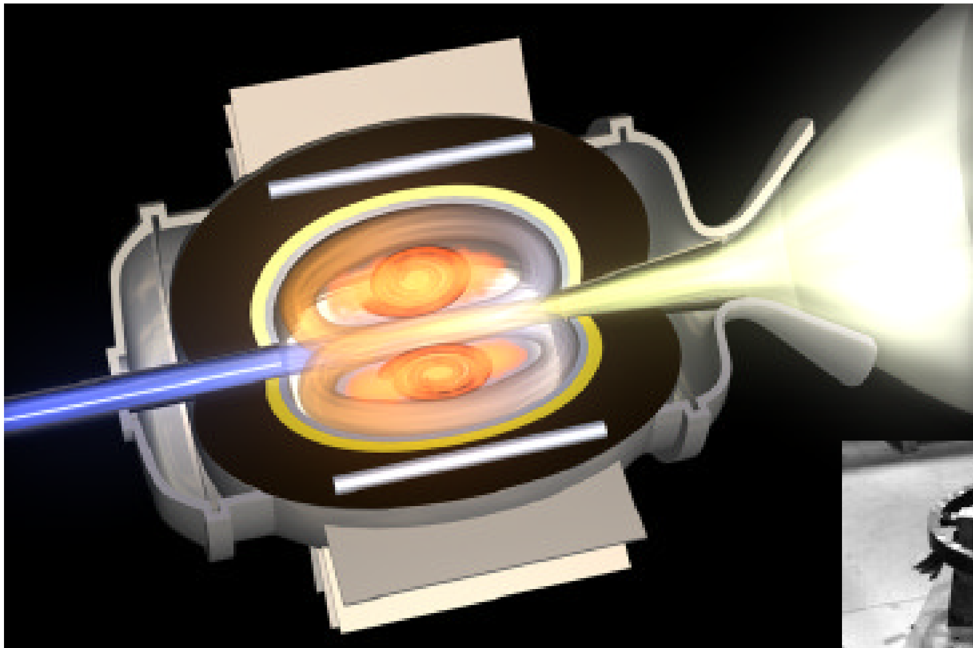


Lox Augmented Nuclear Thermal Rocket (LANTR)



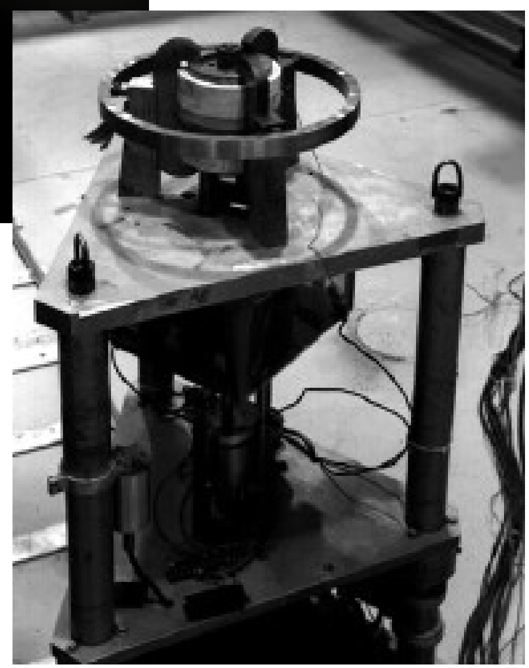
(U,Zr,Nb)C Sample During Sintering

Advanced Nuclear Propulsion Concepts Cont'd

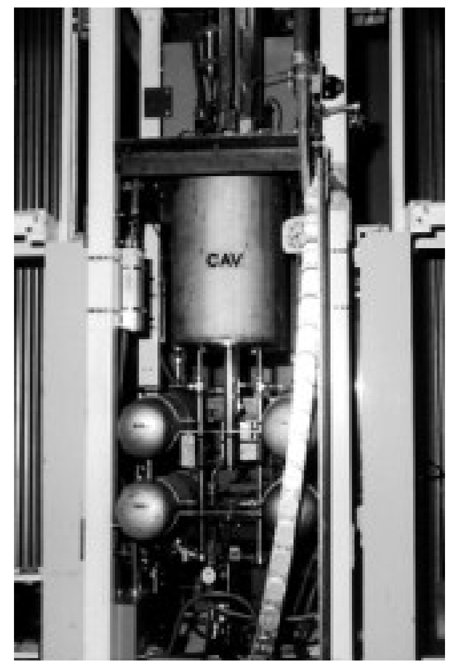


- **Gas Core NTR**
  - Hydrogen gas heated to these very high temperatures may provide Isp > 3000 sec.
  - Los Alamos and Brooklyn Polytechnic Institute have mathematically simulated confinement flow patterns that retain the uranium fuel while releasing the high pressure hydrogen through the nozzle.

- **Pulsed Nuclear Reactors**
  - Reactors that operate in a pulsed mode have been developed by Los Alamos and Sandia for studying the effects of of nuclear weapons bursts.
  - The very high temperatures of the pulse could, in principle, provide very high Isp , but the low pulse repetition frequency may limit its use for propulsion



Godiva

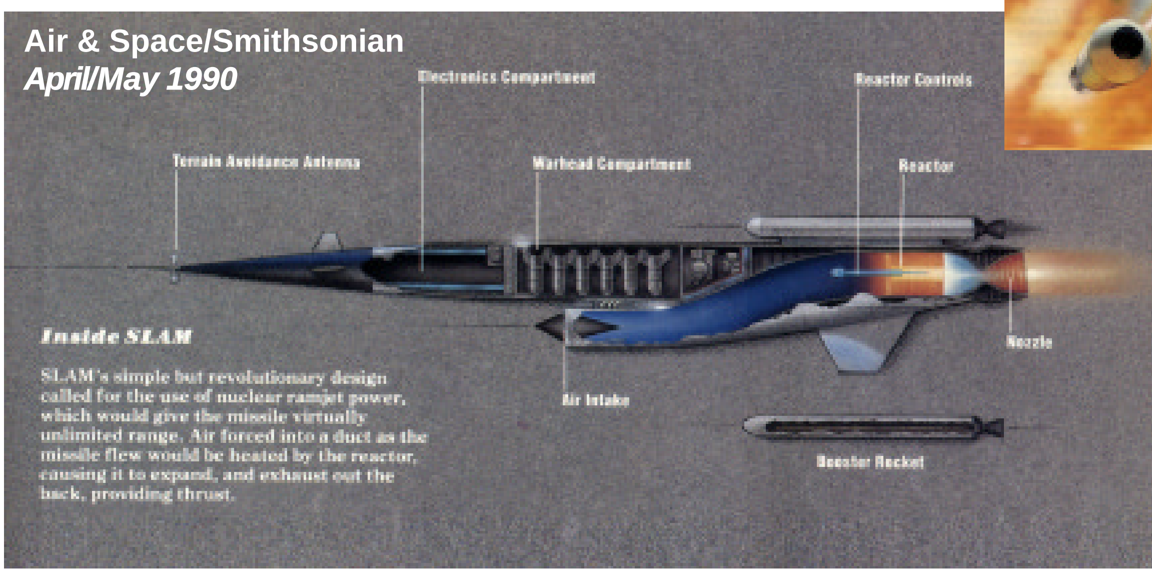


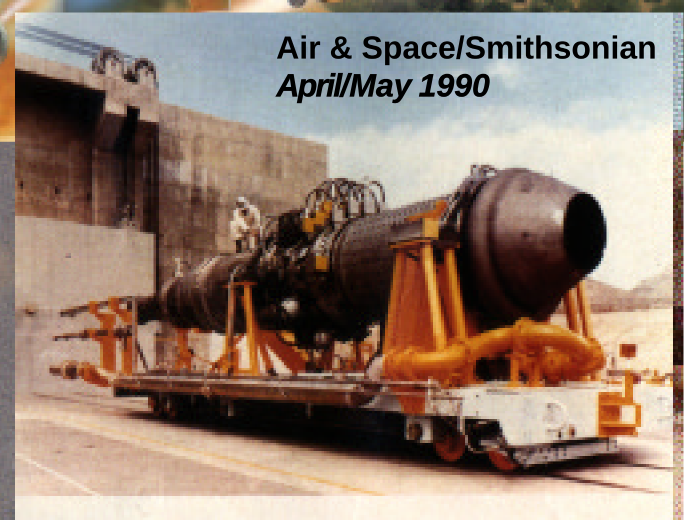
Sheba

Los Alamos Pulsed Nuclear Reactors

Advanced Nuclear Propulsion Concepts

- **Pluto - Nuclear Ramjet - ABCC**
  - During the "60s Livermore successfully demonstrated a proof of concept nuclear powered ramjet that traveled on a track in the Nevada Test Site. The air heat exchanger material was developed by the Coor's brewery.
  - This project was discontinued after successfully completing all their development objectives.
  - An Atomic Based Combined Cycle concept might make an impressive vehicle for the next generation of planetary airplanes, perhaps flying through Jupiter's atmosphere for several years.

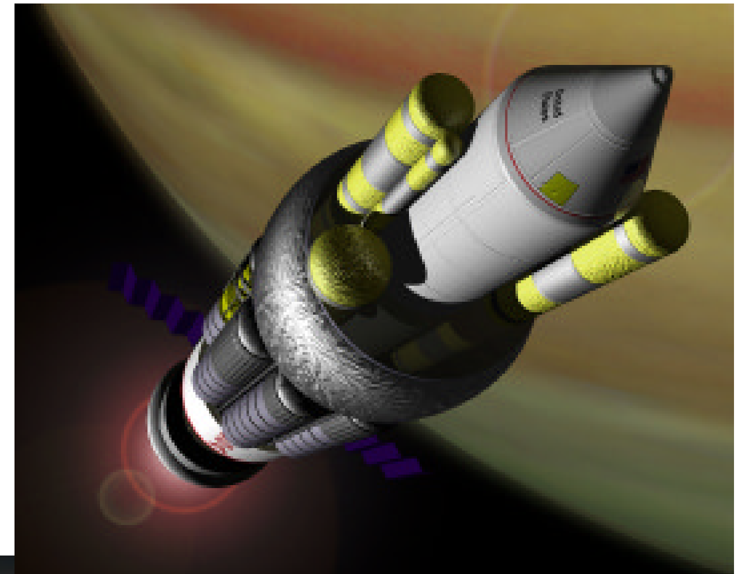




Mounted on a railroad car, Tory-IIC is readied for its highly successful May 1964 test.

Advanced Nuclear Propulsion Concepts Cont'd

- **Orion - A Pulsed Nuclear Concept**
  - Also during the '60s Los Alamos and others simulated a launch vehicle propulsion concept that dropped small nuclear bombs behind a blast shield. Detonation forces on the shield provided a pulsed propulsion. Large shock absorbers were required to control gravity levels, peak gee loads.
  - Isp > 10,000 seconds can be achieved.
  - May require treaty renegotiation.
  - Potential environmental issues for ETO applications.
  - Some research is being conducted by the University of Alabama in Huntsville for deep space applications utilizing components that are not and cannot be assembled into nuclear weapons.
  - The additional radiation added to the interplanetary environment probably could not be detected.
  - A concept with this performance can reduce trip times enough to enable human missions to the moons of the Jupiter or beyond.
  - A recent variation is a concept called Medusa which uses a sail to capture the nuclear blast wind.



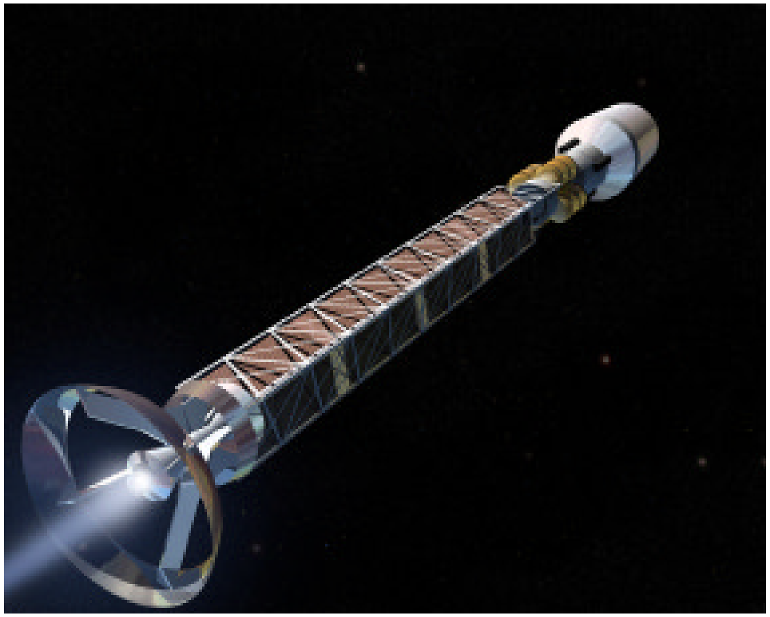
Advanced Nuclear Propulsion Concepts

An Aneutronic Nuclear Ramjet Concept

- For this concept the nuclear fuel is Hafnium, rather than uranium or plutonium. Hafnium is a gamma ray emitter that is susceptible to stimulated emission by soft X-rays.
- The concept vehicle is envisioned to:
  - Take off using hydrocarbon fueled jet engines,
  - Start a nuclear rocket in flight to get through the pinch,
  - Transition to nuclear ramjet, and then
  - Transition to nuclear rocket when leaving the atmosphere.
  - Orbit and de-orbit maneuvers are performed with the nuclear rocket.
  - After reentry a short cruise can be sustained with the hydrocarbon engines, and aerial refueling can extend this range.
  - The vehicle lands on a runway after the reactor has cooled sufficiently.
- The reactor core is radioactive prior to launch before the nuclear engines have been turned on and therefore must be shielded.
- This radiation is gamma rays, which do not cause the vehicle structure to become radioactive like neutrons would.
- The hydrocarbon fuel can contribute to the shielding. The crew compartments, and perhaps the cargo, could be immersed in the fuel tanks
- The residual nuclear fuel can be removed and "burned" in an X-ray chamber to decontaminate it if it is impractical to recycle it.
- In the event of a catastrophe such that the nuclear fuel is dispersed there is a problem since the half-life is 31 years.
- Other alternate nuclear reactions may be possible.

Fusion / Antimatter Propulsion

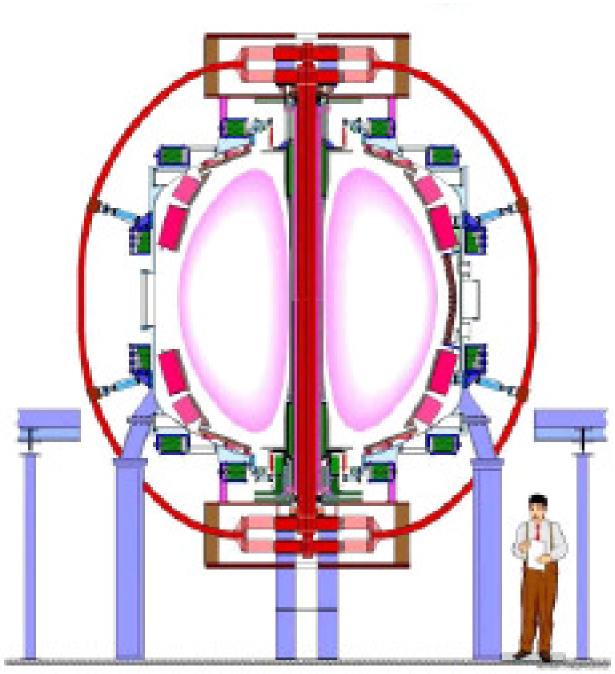
- **Introductory Comments Regarding Fusion Propulsion**
  - Breakeven fusion energy production has not yet been achieved. NSTX experiment may prove the principles that will enable scale up to breakeven conditions.
  - NASA does not intend to try to solve the fusion power production problem.
  - NASA does intend to try to be ready to implement fusion propulsion when it can be.
  - Fusion propulsion promises Isp > 100,000 s, enabling routine human missions anywhere in the solar system at almost any time. To follow our dreams we must pursue this!



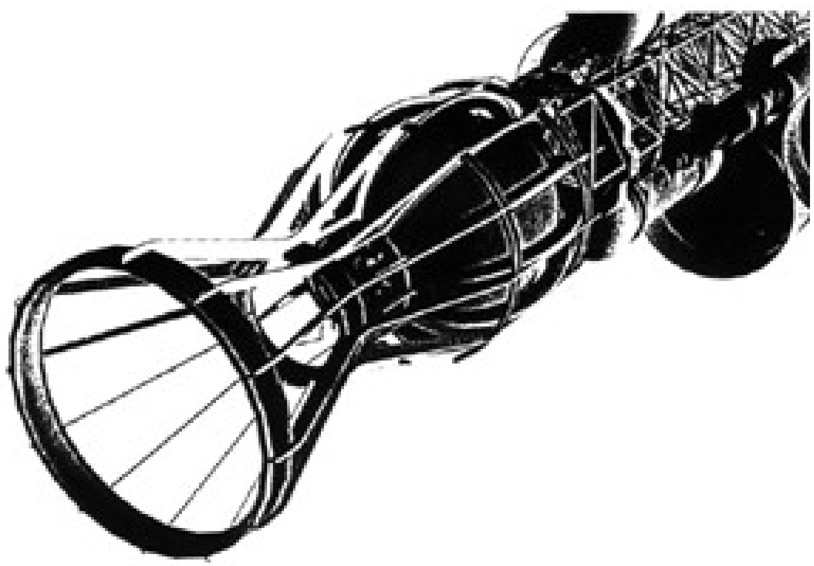
  - Of the thirty or so fusion concepts that have been identified by DOE at least half a dozen can be utilized for propulsion.
  - For as many of these concepts as can be pursued NASA scientists and engineers should learn how to generate and manipulate fusion-like plasmas.
  - NASA plans to utilize the expertise and facilities of the DOE labs and their affiliated universities to the extent that they can be made available within the limited budgets available for this purpose.
  - Fusion propulsion concepts tend to be very heavy and very large. Radiators, other thermal control equipment, magnets, electrical power conditioning equipment, propellant and shielding are the major contributors

Fusion / Antimatter Propulsion

- **National Spherical Torus Experiment (NSTX)**
  - Princeton University is developing the NSTX for DOE to demonstrate the principles that will show that breakeven fusion is feasible.
  - Plasma is put into and removed from the NSTX using a coaxial helicity injector/ejector.
  - A propulsion system based on this concept has been conceptually synthesized by GRC.

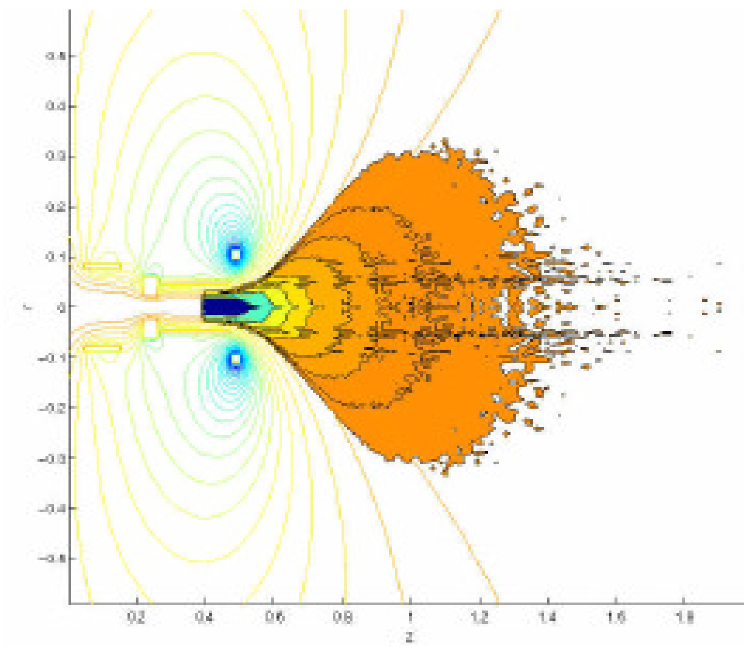


NSTX

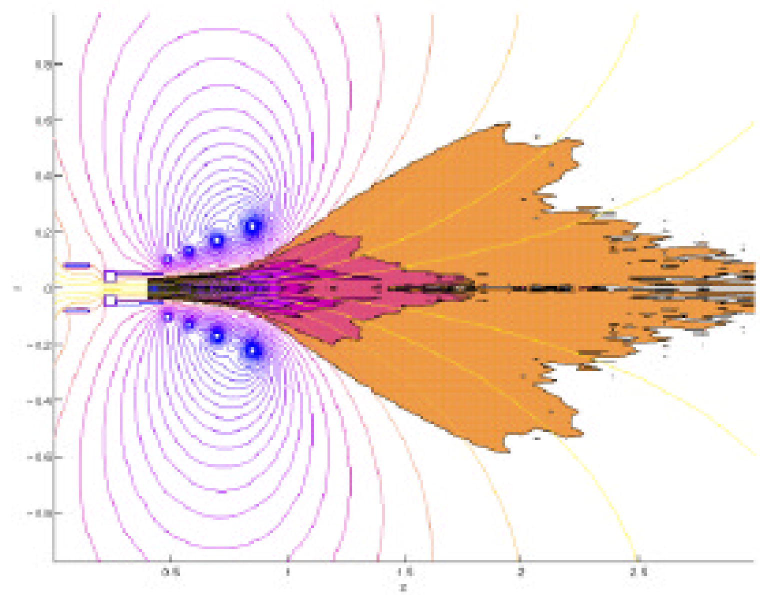


Fusion / Antimatter Propulsion Cont'd

- **Magnetic Nozzles**
  - Fusion plasmas, at 100,000,000 degrees K require magnetic nozzles to guide the exhausted plasmas to provide thrust without evaporating the engine.
  - Ohio State and Los Alamos are working to develop and verify a methodology for designing functional magnetic nozzles for fusion propulsion.
  - Since magnetic field lines are closed, separation of the charged plasma particles from the magnetic fields becomes a problem to avoid magnetic drag.



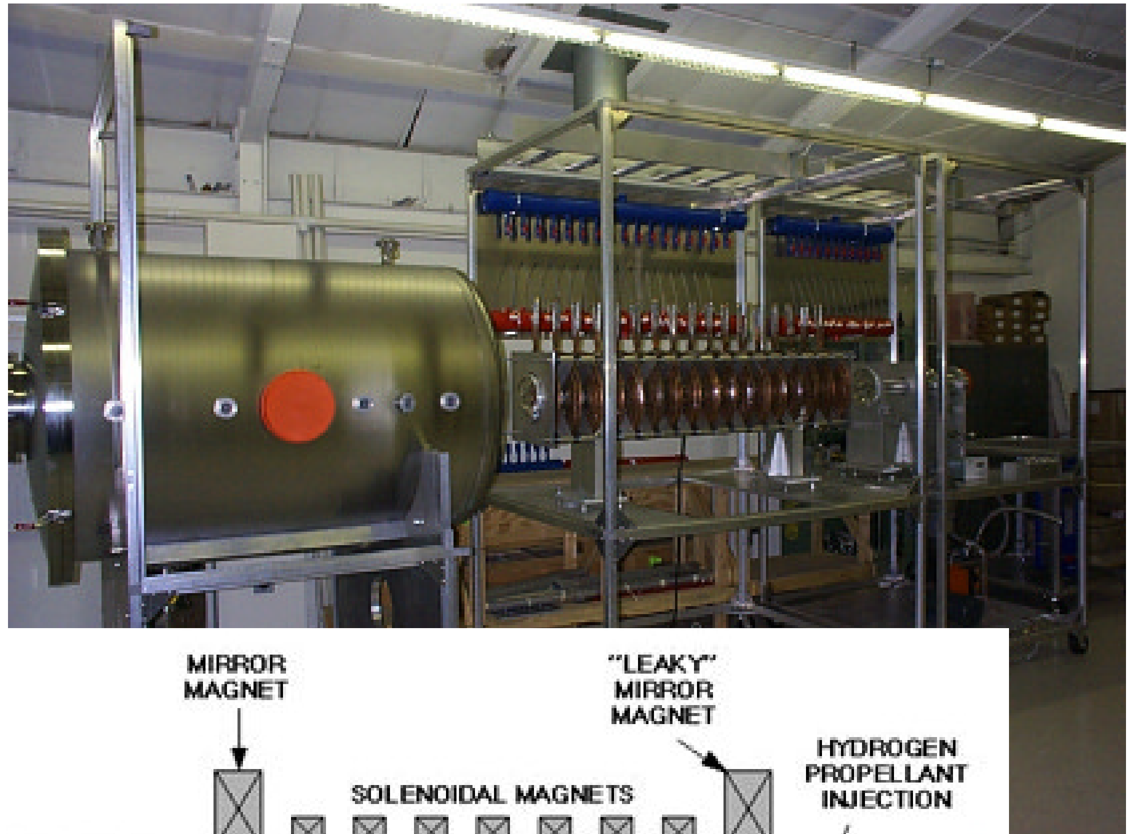
No magnetic shaping, Directivity: .8

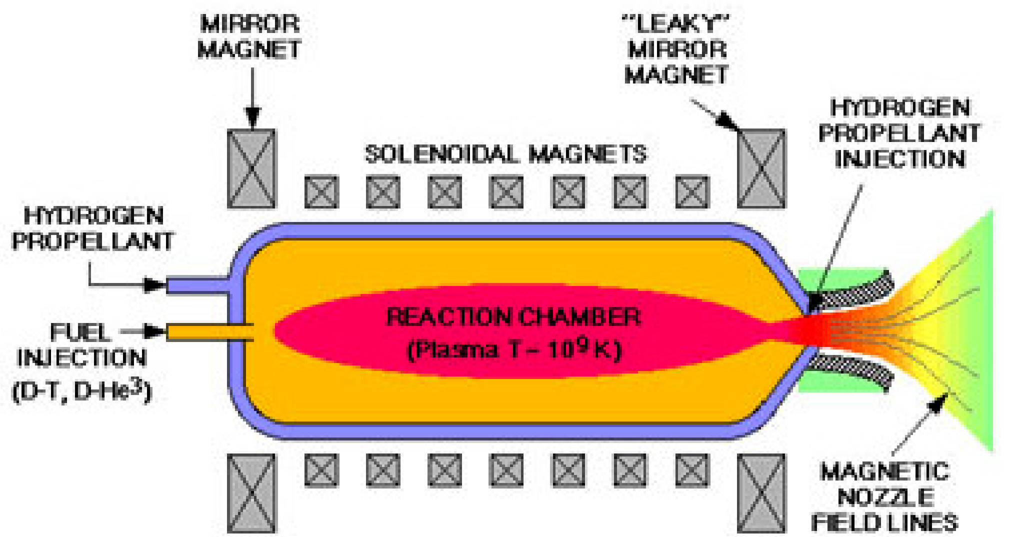


With shaping coils, Directivity: .9

Fusion / Antimatter Propulsion Cont'd

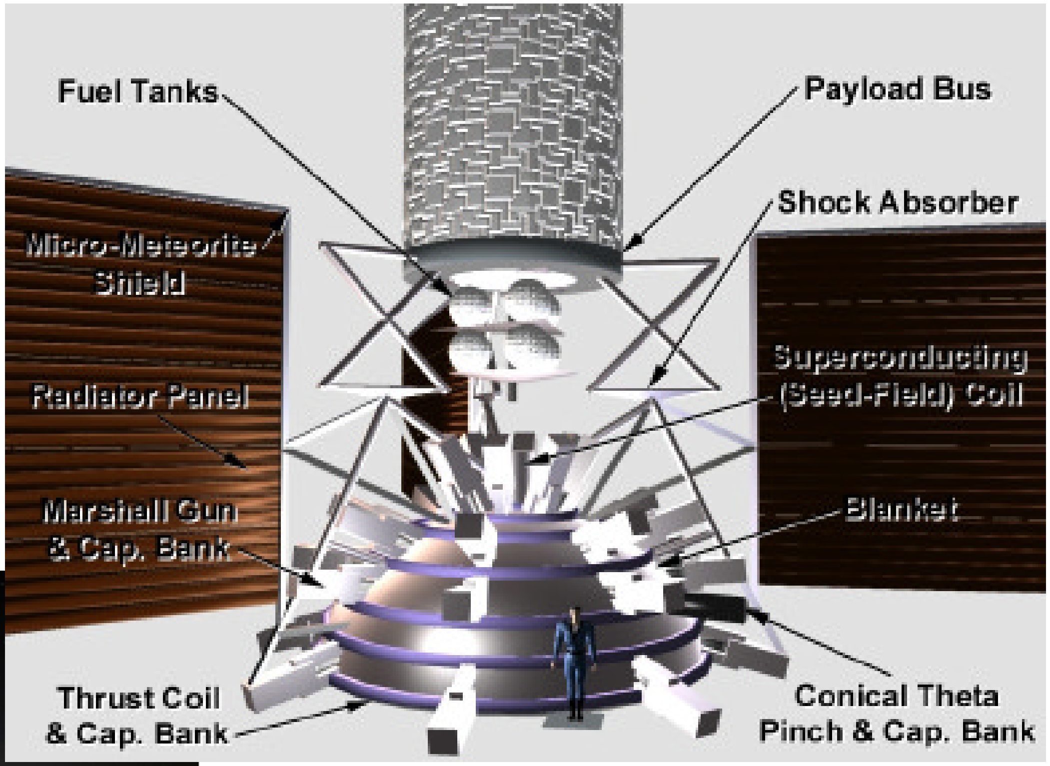
- **Gas Dynamic Mirror**
  - Plasma is injected into a long chamber and tightly confined by magnetic fields very similar to the Plasma Rocket concept mentioned earlier.
  - Pinch magnets at each end reflect the charged plasma particles.
  - The plasma is initially heated by microwaves to very high temperatures.
  - Collisions of the plasma particles cause some fusion to occur which sustains the temperature.
  - The highest energy on-axis particles leak through a mirror magnet providing continuous thrust.

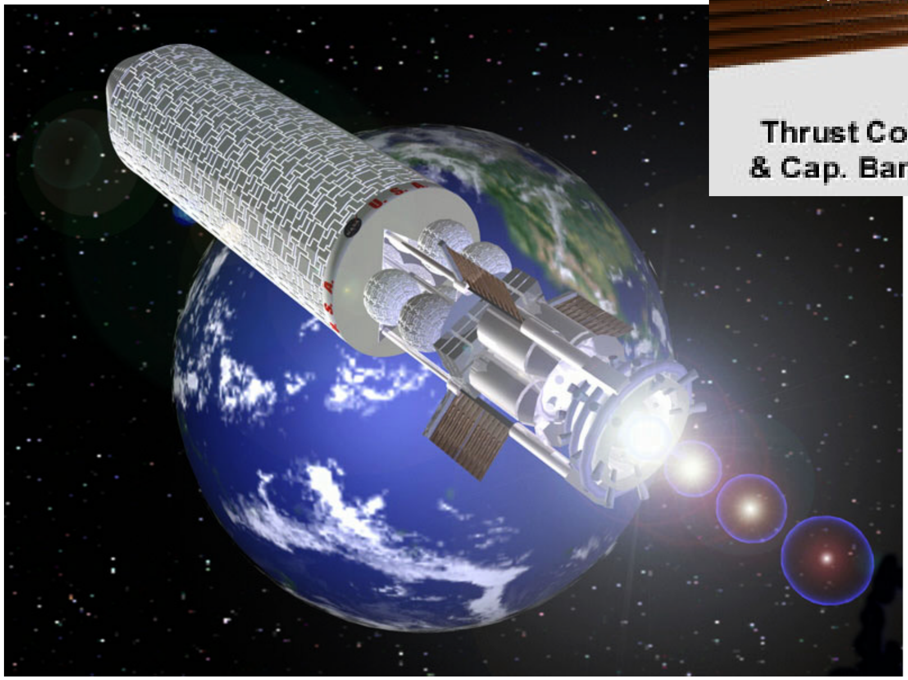




Fusion / Antimatter Propulsion Cont'd

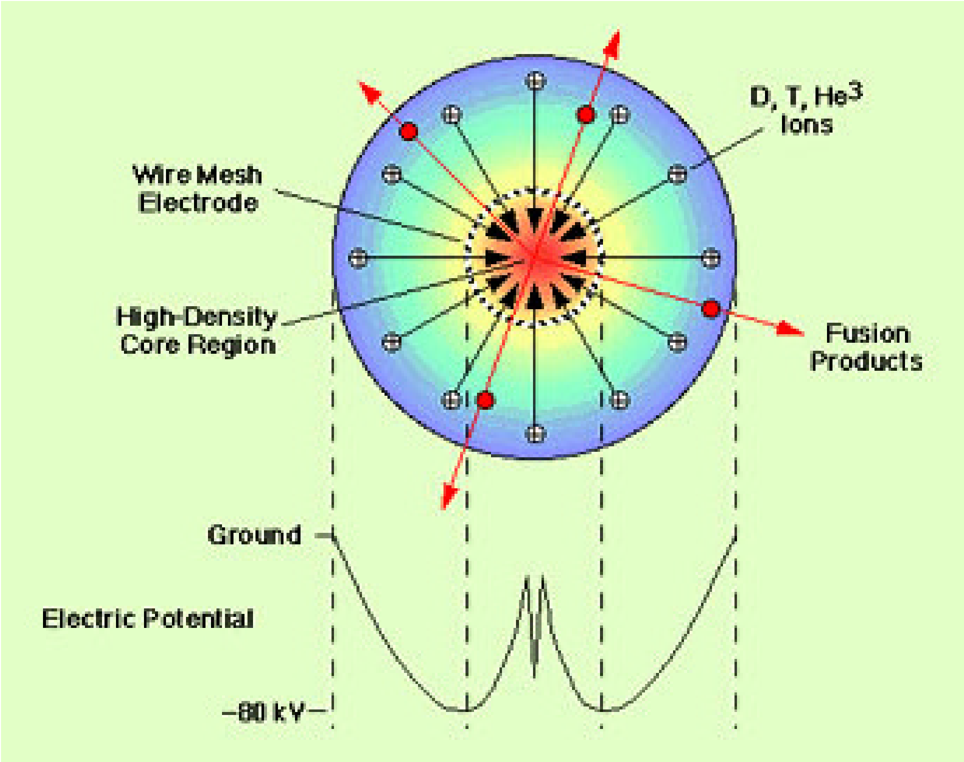
- **Magnetized Target Fusion Propulsion**
  - Similar to the Orion concept, small magnetized targets containing fusionable material are injected out the back of a vehicle.
  - Compression is accomplished via particle beams, lasers, magnetic compression, etc.
  - Fusion occurs, the target detonates providing pressure on a blast shield which generates thrust.

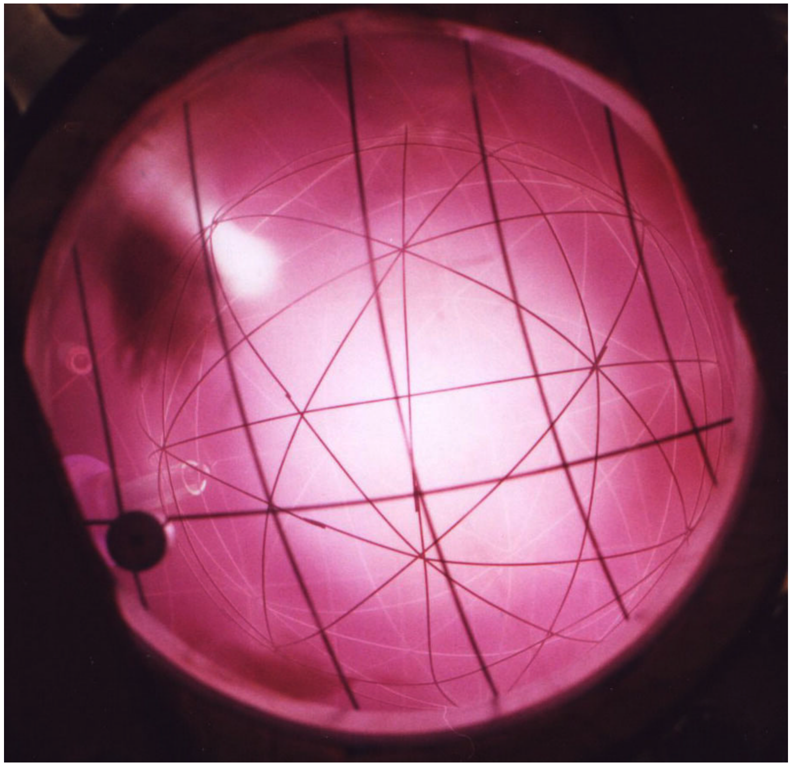




Fusion / Antimatter Propulsion Cont'd

- **Inertial Electrostatic Confinement Fusion Propulsion**
  - Electrically charged wire grids, in a concentric spherical shape, cause the plasma to ossicilate back and forth across the center of the spheres.
  - Collisions at the center of the grids can cause fusion.
  - Control of the grid potential can direct a beam of plasma from the device providing thrust.
  - Devices of this type have actually produced detectable amounts of fusion.

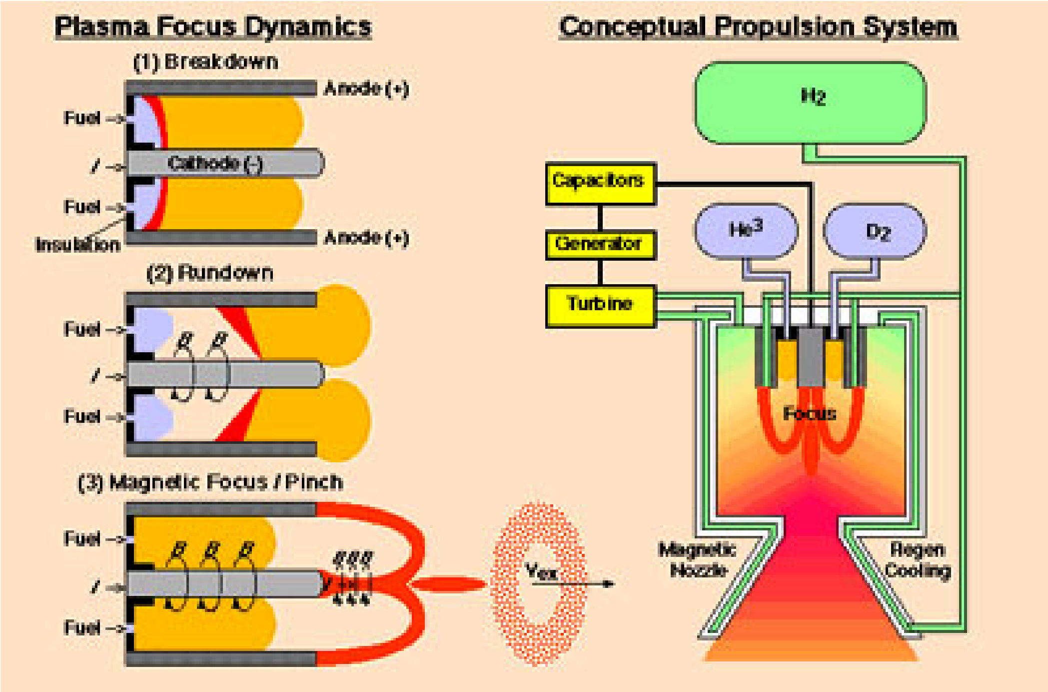




Fusion / Antimatter Propulsion

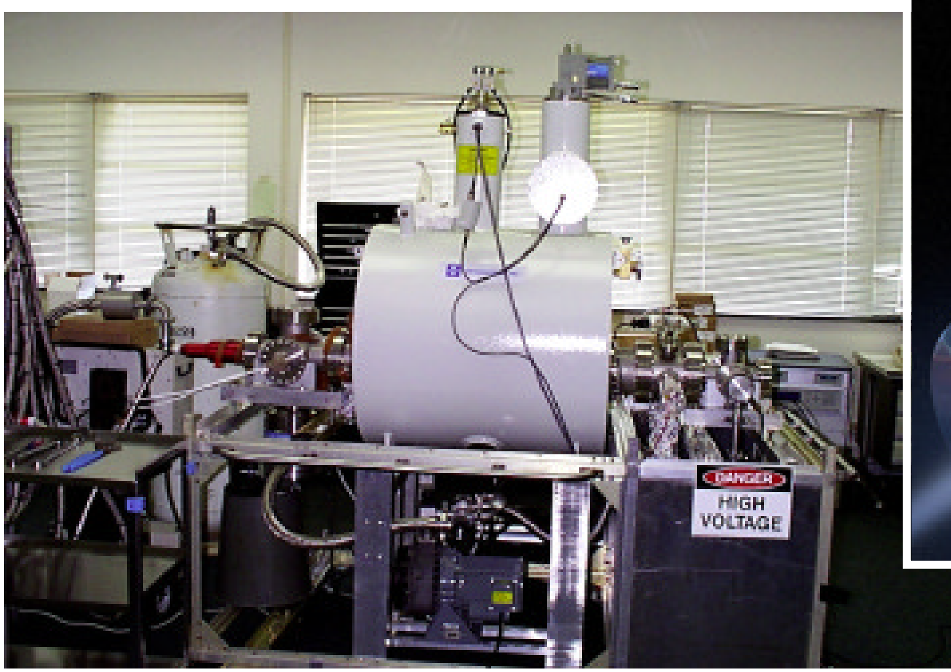
Dense Plasma Focus

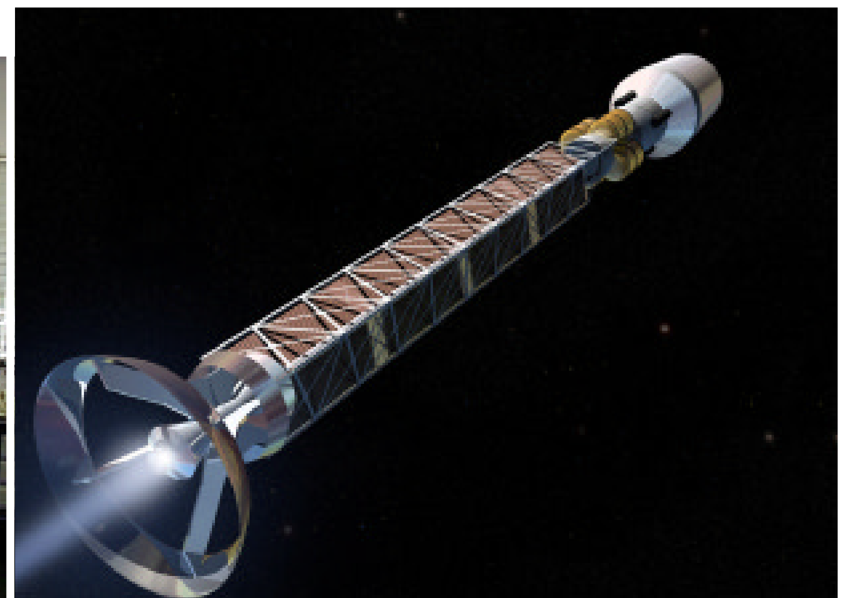
- Plasma exits an MPD thruster as a rotating magnetized toroid , a kind of magnetic bubble which rapidly collapses with extreme pressure.
- Fusionable material caught inside the bubble will undergo fusion releasing detectable levels of neutrons.
- Neutron sources based on this principle are available commercially.
- A breakeven propulsion system would require electrodes several meters in diameter and some clever concepts for controlling electrode erosion and vaporization.
- Avogadro Energy Systems, Inc. of New Jersey has made substantial progress recently towards solving these problems.



Fusion / Antimatter Propulsion Cont'd

- **Antimatter**
  - If the energy from antimatter annihilation can be used for propulsion, one gets an Isp > 2 Million sec.
  - Current methods for producing antiprotons requires 2000 X more energy than can be obtained from it. Furthermore, the very high energy gamma rays emerging from annihilation are difficult to use.
  - Alternatively, small amounts of antimatter may be effective in initiating microfission or microfusion.
  - This latter concept is being studied by MSFC, JPL, Penn State, and the Air Force at Kirtland. A portable antimatter trap that holds 10^8 antiprotons for several days has now been developed and is being tested.

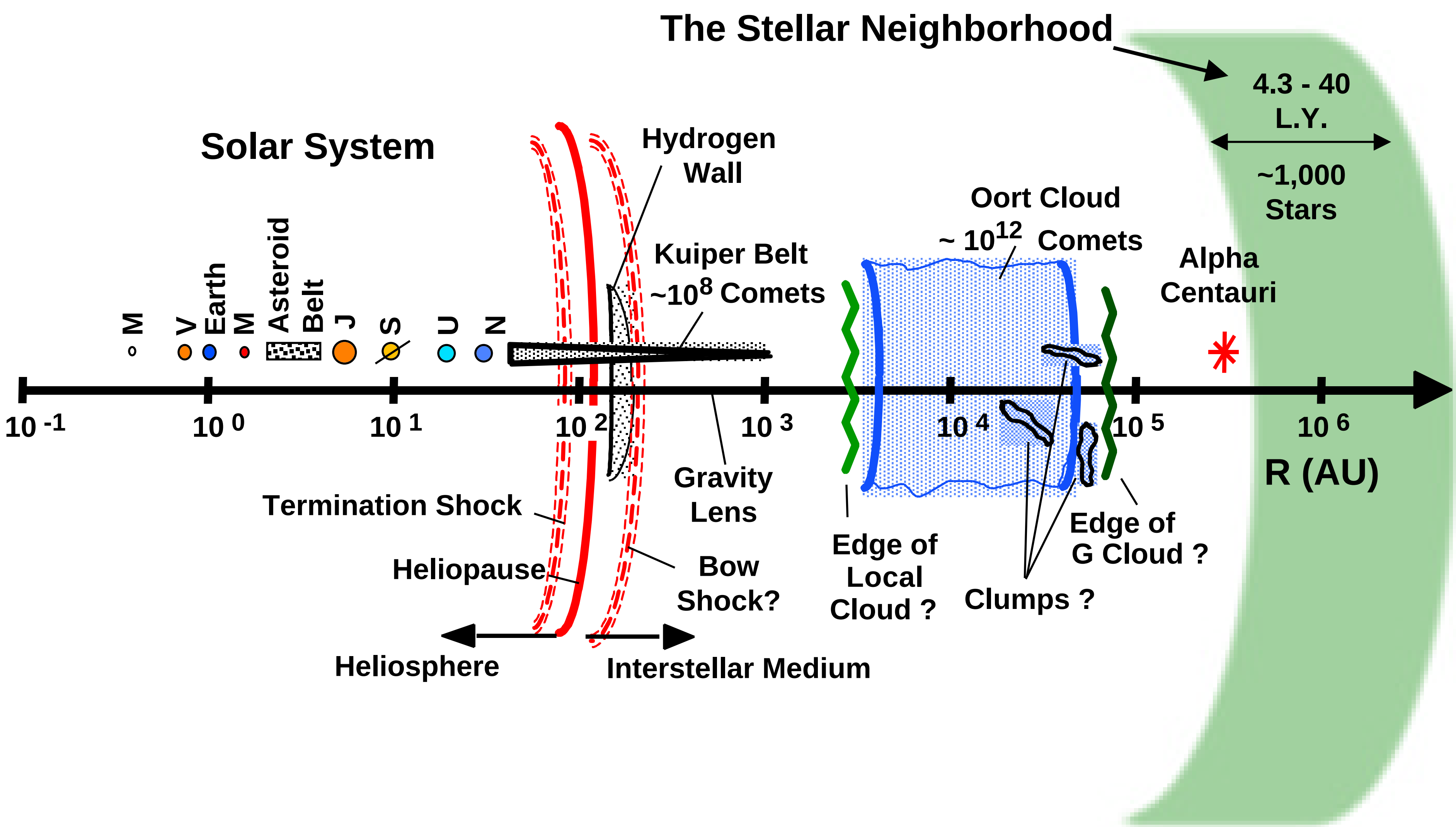




Interstellar Travel

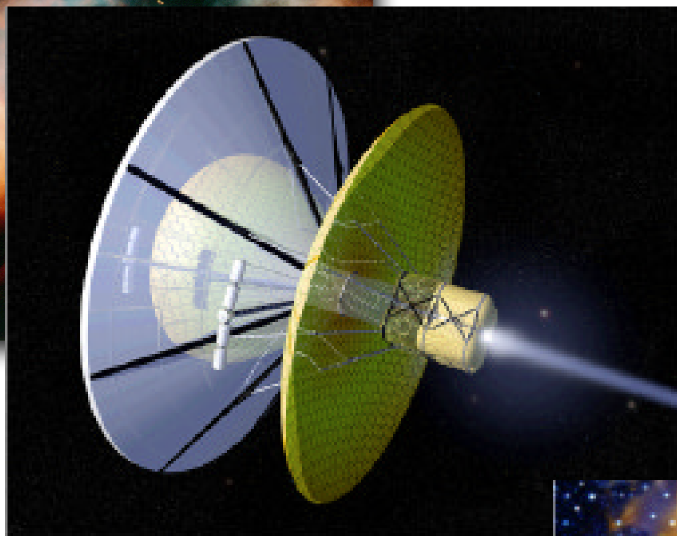
- **Relative Distances**
  - Pluto is at 39 AU, Voyager is now at about 69 AU, The Kuiper Belt extends to 100 AU, The Oort Cloud may extend to 10,000 AU,
  - Alpha Centauri is about 250,000 AU, 8 stars within 500,000 AU, 60 stars within 1,000,000 AU.
- **Performance Requirements**
  - To travel 4 light years within 40 years requires acceleration to an average speed of 0.1 c.
  - To rendezvous one must decelerate from this speed.
  - A 40 year single stage Alpha Centauri rendezvous rocket type vehicle requires an Isp > 4 Million sec with a mass fraction of 97%.
- **Concepts (all have serious problems)**
  - Multi-stage fusion or antimatter rockets - staging fractions > 1000.
  - Bussard fusion ramjet - no concepts known for scooping and fusing interstellar hydrogen.
  - Laser sail - feasible in principle, very large components are difficult to deploy and control.
- **Plans**
  - Initial focus on interstellar precursor missions - beyond Pluto.
  - Use solar sail or nuclear electric.
  - Interstellar Precursor Missions being studied by JPL and MSFC.

Nearby Interstellar Targets of Interest



(Mewaldt,1998)

Interstellar Travel Cont'd



Matter-Antimatter

(Highest Energy Density Propellant)

- Production, handling and storage
- Converting energy to propulsion

Fusion Ramjet

(Refueling on the Road)

- H-H fusion
- Large area magnetic scoops
- "Drag-free" fusion

Beamed Energy

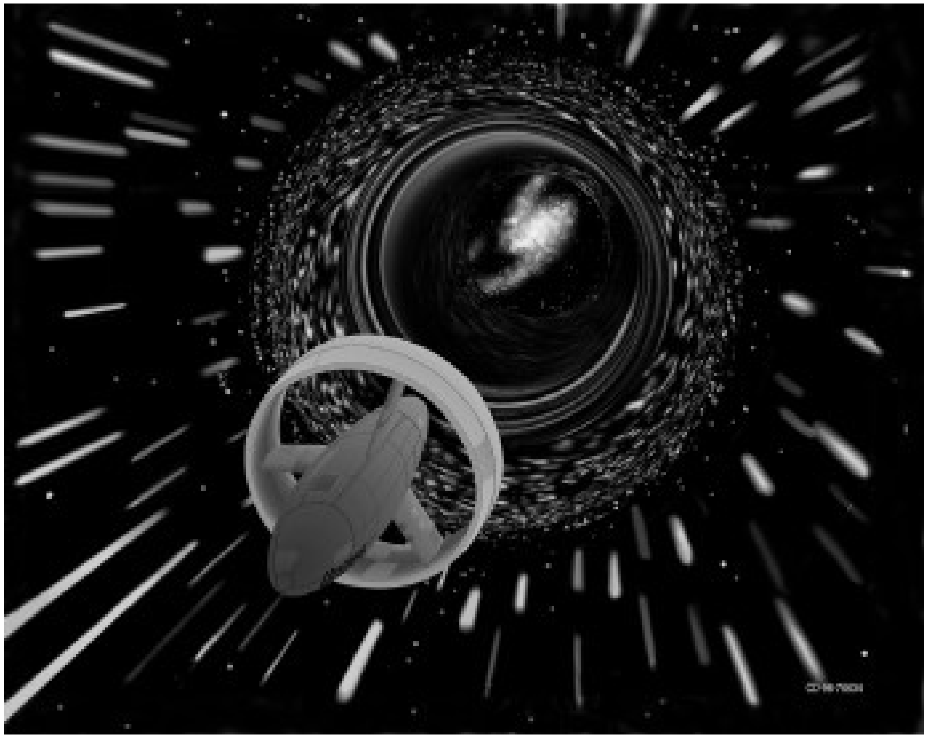
(Propellantless Propulsion)

- Very high power lasers with large apertures
- Precision pointing
- Large, low density sails

Breakthrough Propulsion Physics

- **Recent Interesting Experiments or Hypotheses**
  - Gravity Manipulation
  - Zero-Point energy from vacuum quantum fluctuations
  - Origin of inertia from scattering of vacuum fluctuations
  - Superluminal velocities
  - Space warp and wormholes

- **NASA may be interested IF all the following criteria are met:**
  - Experiments and hypotheses have been developed by those with appropriate academic credentials.
  - A peer reviewed theory exists that explains and predicts the effects.
  - There is a connection to space transportation.
  - A low cost definitive experiment can be devised that can be performed within two or three years.



- **Glenn Research Center manages the Breakthrough Propulsion Physics Project**
  - A recent NRA selected and initiated several research activities.
  - http://www.grc.nasa.gov/www/bpp/

Conclusion

- **This has been a brief discussion of some of the current advanced propulsion research.**
- **The areas covered included:**
  - Advanced Chemical
  - Electromagnetic
  - Nuclear
  - Fusion / Antimatter
  - Interstellar
  - Breakthrough Propulsion Physics
- **Exciting possibilities lie ahead!**
- **These and other similar charts may soon be found as a part of:**
  - http://stp.msfc.nasa.gov
  - See also:
    - http:// sec353.jpl.nasa.gov
    - http://niac.usra.edu
    - http://www.grc.nasa.gov/www/bpp